This is a digital copy of a book that was preserved for generations on library shelves before it was carefully scanned by Google as part of a project to make the world's books discoverable online.

It has survived long enough for the copyright to expire and the book to enter the public domain. A public domain book is one that was never subject to copyright or whose legal copyright term has expired. Whether a book is in the public domain may vary country to country. Public domain books are our gateways to the past, representing a wealth of history, culture and knowledge that's often difficult to discover.

Marks, notations and other marginalia present in the original volume will appear in this file - a reminder of this book's long journey from the publisher to a library and finally to you.

Usage guidelines

Google is proud to partner with libraries to digitize public domain materials and make them widely accessible. Public domain books belong to the public and we are merely their custodians. Nevertheless, this work is expensive, so in order to keep providing this resource, we have taken steps to prevent abuse by commercial parties, including placing technical restrictions on automated querying.

We also ask that you:

+ *Make non-commercial use of the files* We designed Google Book Search for use by individuals, and we request that you use these files for personal, non-commercial purposes.

+ *Refrain from automated querying* Do not send automated queries of any sort to Google's system: If you are conducting research on machine translation, optical character recognition or other areas where access to a large amount of text is helpful, please contact us. We encourage the use of public domain materials for these purposes and may be able to help.

+ *Maintain attribution* The Google "watermark" you see on each file is essential for informing people about this project and helping them find additional materials through Google Book Search. Please do not remove it.

+ *Keep it legal* Whatever your use, remember that you are responsible for ensuring that what you are doing is legal. Do not assume that just because we believe a book is in the public domain for users in the United States, that the work is also in the public domain for users in other countries. Whether a book is still in copyright varies from country to country, and we can't offer guidance on whether any specific use of any specific book is allowed. Please do not assume that a book's appearance in Google Book Search means it can be used in any manner anywhere in the world. Copyright infringement liability can be quite severe.

About Google Book Search

Google's mission is to organize the world's information and to make it universally accessible and useful. Google Book Search helps readers discover the world's books while helping authors and publishers reach new audiences. You can search through the full text of this book on the web at `http://books.google.com/`

LIBRARY OF THE
UNIVERSITY OF MICHIGAN

DEPARTMENT
OF
ENGINEERING

DYNAMO-ELECTRIC MACHINERY

A Manual for Students of Electrotechnics

BY

hillips

SILVANUS P. THOMPSON, D.Sc. B.A. F.R.S.

PRINCIPAL OF, AND PROFESSOR OF PHYSICS IN THE
CITY AND GUILDS OF LONDON TECHNICAL COLLEGE, FINSBURY;
PAST-PRESIDENT OF THE INSTITUTION OF ELECTRICAL ENGINEERS

SEVENTH EDITION

VOLUME I.

CONTINUOUS-CURRENT MACHINES

29

London:
E. & F. N. SPON, LTD., 125 STRAND
New York:
SPON & CHAMBERLAIN, 123 LIBERTY STREET
1904

M

PREFACE

THE last English edition of this work (the fifth) appeared in 1896. The sixth edition, published only in America, differed merely in the addition of a supplement relating to American machines. With the development of the subject it has become necessary to divide the work into two parts. Hence the present volume, Part I. of the Seventh Edition, deals only with machinery for Continuous-Currents. Part II., dealing with machinery for Alternating-Currents, is in the press and will be published in 1904.

The long delay in the publication of the present edition is due to many causes. In particular, full twelve months of delay have been occasioned by a libel suit brought against the author on account mainly of statements which have appeared substantially without change in every edition of this book since 1884.

The author's grateful acknowledgments are once again due to the many engineers and manufacturing firms who have favoured him with information, data, and drawings used in the preparation of this work. To particularize them here would be to name a large proportion of the leading electrical firms and engineers of Europe. Acknowledgments are made

148314

in the text; but lest any may have been inadvertently omitted the author here desires to express a general recognition.

The author is glad to be able to acknowledge the personal help he has received in the revision of his work from his former assistants, Mr. J. Dennis Coales, B.Sc., and Mr. Fielder I. Hiss, as well as from his present assistant, Mr. H. W. Taylor. Nor would his acknowledgments be complete without adding the name of Mr. A. C. Eborall, who nearly four years ago helped the author with matter now embodied in Chapters XVII. and XIX., as well as in the revision of some earlier portions. The section on Controllers in Chapter XXVI. is largely due to Mr. Taylor; that on Boosters in Chapter XXIV. to Mr. Hiss.

The chapters on Dynamo Design, which were published a year ago as a separate book, are now, as originally intended, embodied in the present work.

S. P. T.

LONDON:
October, 1903.

CONTENTS

CHAPTER I.

PAGE
INTRODUCTORY 1

CHAPTER II.

HISTORICAL NOTES 7

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES 37

CHAPTER IV.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON 71

CHAPTER V.

FORMS OF FIELD-MAGNETS 115

CHAPTER VI.

MAGNETIC CALCULATIONS AS APPLIED TO DYNAMO MACHINES 130

CHAPTER VII.

COPPER CALCULATIONS; COIL WINDINGS 155

CHAPTER VIII.

PAGE
INSULATING MATERIALS AND THEIR PROPERTIES 189

CHAPTER IX.

ACTIONS AND REACTIONS IN THE ARMATURE 197

CHAPTER X.

COMMUTATION; CONDITIONS OF SUPPRESSION OF SPARKING .. 235

CHAPTER XI.

ELEMENTARY THEORY OF THE DYNAMO, MAGNETO, AND SEPARATELY-EXCITED MACHINES. SELF-EXCITING MACHINES 279

CHAPTER XII.

CHARACTERISTIC CURVES 321

CHAPTER XIII.

THE THEORY OF ARMATURE WINDING 350

CHAPTER XIV.

ARMATURE CONSTRUCTION 422

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION 467

CHAPTER XVI.

COMMUTATORS, BRUSHES AND BRUSH-HOLDERS 481

CHAPTER XVII.

PAGE
LOSSES, HEATING AND PRESSURE-DROP 512

CHAPTER XVIII.

THE DESIGN OF CONTINUOUS-CURRENT DYNAMOS 532

CHAPTER XIX.

ANALYSIS OF DYNAMO DESIGN 582

CHAPTER XX.

EXAMPLES OF MODERN DYNAMOS (LIGHTING AND TRACTION) 650

CHAPTER XXI.

DYNAMOS FOR ELECTRO-METALLURGY AND ELECTRO-PLATING 703

CHAPTER XXII.

ARC-LIGHTING DYNAMOS AND RECTIFIERS 726

CHAPTER XXIII.

SPECIAL TYPES OF DYNAMOS: EXTRA HIGH VOLTAGE MACHINES, STEAM-TURBINE MACHINES, EXTRA LOW SPEED MACHINES, EXCITERS, DOUBLE-CURRENT MACHINES, THREE-WIRE MACHINES, HOMOPOLAR (UNIPOLAR) MACHINES, DISK DYNAMOS 752

CHAPTER XXIV.

MOTOR-GENERATORS AND BOOSTERS 772

CHAPTER XXV.

PAGE
CONTINUOUS-CURRENT MOTORS 792

CHAPTER XXVI.

REGULATORS, RHEOSTATS, CONTROLLERS AND STARTERS .. 869

CHAPTER XXVII.

MANAGEMENT AND TESTING OF DYNAMOS 913

APPENDIX.

WIRE GAUGE TABLES .. .. *To face p.* 940

INDEX 941

LIST OF PLATES

SUBJECT — DESCRIBED AT PAGE

I. CURVES OF MAGNETIC DATA 85

II. KAPP BIPOLAR DYNAMO (FIELD-MAGNETS AND TRANSVERSE SECTION OF ARMATURE) .. 651

III. ,, ,, (ARMATURE IN LONGITUDINAL SECTION) 651

IV. ,, ,, (ROCKER, BRUSH-HOLDER, AND LUBRICATOR) 651

V. SCOTT AND MOUNTAIN 6-POLE GENERATOR .. .. 582 and 665

VI. KOLBEN 4-POLE GENERATOR 671

VII. BROWN, BOVERI AND CO. 8-POLE ELECTRO-METALLURGICAL GENERATOR (GENERAL VIEW AND BRUSH-ROCKER) .. 609

VIII. BROWN, BOVERI AND CO. 8-POLE ELECTRO-METALLURGICAL GENERATOR (ARMATURE) 609

IX. BROWN'S BARREL-WOUND DRUM ARMATURE .. .. 449 and 662

X. PARSHALL'S 6-POLE TRAMWAY GENERATOR (SECTIONAL VIEWS) .. 675

XI. ,, ,, ,, ,, (COMMUTATOR) 488

XII. PARSHALL'S 10-POLE TRAMWAY GENERATOR 678

XIII. KUMMER'S 18-POLE TRAMWAY GENERATOR 686

XIV. ALLGEMEINE ELEKTRIZITÄTS GESELLSCHAFT, 14-POLE GENERATOR FOR ELECTRO-CHEMICAL WORK 715

XV. OERLIKON 4-POLE GENERATOR (CENTRAL LONDON RAILWAY) 652

SUBJECT — DESCRIBED AT PAGE
XVI. KOLBEN'S 10-POLE TRACTION GENERATOR (GENERAL VIEW) 671
XVII. ,, ,, ,, ,, (ARMATURE) .. 401
XVIII. ,, ,, ,, ,, (MAGNET BOBBIN) 671
XIX. OERLIKON 12-POLE TRACTION GENERATOR 654
XX. POSTEL-VINAY 12-POLE (RING) GENERATOR 686
XXI. KOLBEN'S 18-POLE ELECTROLYTIC GENERATOR 718
XXII. GANZ AND CO. 6-POLE MARINE GENERATOR (GENERAL VIEW) 689
XXIII. ,, ,, ,, ,, (COMMUTATOR, AND POLE-CORES) 492 and 269
XXIV. INTERNATIONAL ELECTRIC CO. 8-POLE GENERATOR .. 695
XXV. SIEMENS AND HALSKE'S GENERATORS 687
XXVI. ALIOTH'S 12-POLE (RING) ELECTROLYTIC GENERATOR .. 720
XXVII. SHAFTS OF VARIOUS MACHINES 473
XXVIII. TRAMWAY MOTOR OF SOC. ÉLECTRICITÉ ET HYDRAULIQUE 857
XXIX. THURY'S VERTICAL SHAFT MOTOR 866
XXX. LAHMEYER'S BOOSTER 789

DYNAMO-ELECTRIC MACHINERY.

CHAPTER I.

INTRODUCTORY.

THE term "dynamo-electric machine" was originated, so far as the English language is concerned, by the late Mr. Charles Brooke, F.R.S., as recorded[1] on page 409, vol. xv. of the *Proceedings* of the Royal Society in 1867, in a paper on the conversion of energy. In recent years the term has been used in its general sense to include all machines, the action of which is dependent on the principle of *induction*,[2] discovered by Faraday in 1831. Faraday himself called such machines *magneto-electric*, and this adjective is still retained to denote those having a permanent magnet of steel, though

---

[1] "The dynamic nature of electric energy is clearly indicated by the dynamo-electric machine of Holtz, in which dynamic is directly converted into electric energy,—and by the cognate machines of Wilde, Wheatstone, Siemens and Ladd, in all of which alike there is an intervening conversion of dynamic into magnetic energy." Brooke goes on, in a footnote, to explain the definite principle governing the construction of those compound terms which must be constantly employed in relation to the conversions of energy. "This," he says, "may be accomplished by taking the first section of the term to mean the *acting cause*, the second the *resulting effect*: thus a dynamo-electric machine will be one in which dynamic energy is employed to produce an electric current; and an electro-dynamic engine, one in which a current is employed to evolve dynamic energy." But no subsequent writer has ever regarded any machines that depend (like those of Holtz and Wimshurst) on purely electrostatic operations as included under the term dynamo-electric.

[2] *Induction* means the inducing of electromotive force. The term originated with Faraday himself.

"Then I found that magnets would *induce* just like voltaic currents, and by bringing helices and wires and jackets up to the poles of magnets, electrical currents were *induced* in them. . . . These two kinds of *induction* I have

2.

Faraday applied it alike to cases in which steel bars, lodestones, electro-magnets, and even the earth were used as magnets. In some dynamo machines the conductors move, while the magnets are stationary; in others the magnets move, while the conductors stand still; in others both parts move; while again in others neither move, but the induction is effected by the movement of masses of iron. Hence the more general statement:—

A dynamo-electric machine is a machine for converting mechanical energy into energy in the form of electric currents, or vice versâ, by magneto-electric induction; the operation being in general that of causing conductors (usually of copper) *to cut magnetic lines.*

Every dynamo-electric machine is, however, capable of serving two distinct functions, the converse of one another. When supplied with mechanical power from some external source of power, such as a steam-engine, it furnishes electric currents. When supplied with electric currents from some external source, such as a voltaic battery, it furnishes mechanical power. On the one hand the dynamo serves as a *generator*, on the other hand as a *motor*. They are also distinguished, according to the nature of the current which they are to supply, whether *continuous* (*i.e.* uni-directional in flow) or *alternating* (*i.e.* rapidly reversing the direction of the flow). Hence there are four classes of machines—(*a*) continuous-current dynamos; (*b*) alternate-current dynamos, alternators; (*c*) continuous-current motors; (*d*) alternate-current motors. In the case of alternate-current machines, there is a further subdivision into those which work with single-phase currents, and those which work with two or three currents in different phases. We shall also have to consider machinery or apparatus for transforming currents of one species into currents of a different species,

---

distinguished by the term volta-electric and magneto-electric *induction*."—Faraday to R. Phillips, Nov. 1831.

Though Faraday thus fixed the meaning of the term "induction" as the *operation* of inducing, a number of recent writers, including Hopkinson, have followed the unfortunate example set by Maxwell in using the term in a different sense to mean the density of the magnetic flux. This ought to be avoided.

or into a different variety of the same species. Such apparatus is of several different kinds, including the alternate-current *transformer*, which is a stationary apparatus, and a number of revolving machines variously known as *motor-generators*, *continuous-current transformers*, *rotatory converters*, *permutators* and *boosters*. In general, every dynamo, whether intended for use as a generator or as a motor, consists of two essential parts, a *field-magnet*, usually a massive, stationary structure of iron surrounded by coils of insulated copper wire, and an *armature*, a peculiarly arranged system of copper conductors, usually wound upon the periphery of a ring, drum, or disk, fixed upon a shaft whereby rotation can be imparted mechanically. The ordinary machines fall under two types :—the "A" type having stationary field-magnet and revolving armature ; this type being universal for all continuous-current generators and motors, and also common for alternate-current generators of low voltage : the " B " type having revolving field-magnets and stationary armature ; this type being now preferred for all large high-voltage alternators. In modern alternate-current motors there is a special type known as the *induction motor*, consisting of a *primary* or *stator* part, and a *secondary* or *rotor* part. The stator (usually stationary) being a true armature receiving its currents from the line, as all motors do ; while the rotor (usually revolving) acts as a sort of field-magnet receiving its magnetism by induction only. There are also special devices for receiving the electric currents from the armature and imparting them to the electric circuit, or *vice versâ*, known as *collectors* or *commutators*, attached to the armature and rotating with it, and collecting *brushes*, constituting sliding circuit-connexions, which press upon the moving surface of the collector or commutator. In those cases where the collecting brush slides from one piece of metal to another, thereby changing the connexions of the circuits, the revolving part is known as the *commutator*. In those cases where there is no change of connexions, but merely sliding contact with one and the same piece of metal, the parts are known as *slip-rings* or *collecting-rings*.

The function of the field-magnet is to provide a *magnetic field* of great extent and density; that is to say, to provide a great flux of magnetic lines through the space wherein the armature conductors are to revolve. It must consequently consist of a large and well-designed, and therefore powerful, magnet or electromagnet, or of a group of such electromagnets, having poles so shaped that the magnetic lines that issue from them shall be utilised in the armature space. The magnetic field and the magnetic properties of iron are dealt with in Chapter IV.; the fundamental principles of the magnetic circuit, including the designing of field-magnets, are dealt with in Chapters V. and VI.

The function of the armature (if rotatory) is to rotate in the magnetic field, whilst carrying electric currents in' its copper coils or conductors; and, while so rotating, to generate electromotive forces by the operation of "cutting" the magnetic lines; or (if stationary) to "cut" the magnetic lines of the revolving poles of the field-magnet. That part ought to be called "armature" which, whether revolving or stationary, is connected to the mains, giving the current to them when the machine is used as a generator, or, when used as a motor, receiving from them the current which drives the machine.

It must be remembered that there is a twofold action between a conducting wire (forming part of a circuit) and a magnetic field. *Firstly*, if the conducting wire is forcibly moved across the magnetic field (so as to cut across the magnetic lines), electric currents are generated in the conductor, and a mechanical effort is required to move the conductor. This is the action discovered by Faraday and termed "magneto-electric induction." In every case the induction or generation of currents necessitates the application of mechanical power and the expenditure of energy. This is the principle of the dynamo *used as a generator*. *Secondly*, if the conducting wire, while situated in the magnetic field, is actually conveying an electric current (from whatever source) it experiences a lateral thrust, tending to move it forcibly, parallel to itself, across the magnetic lines, and so enables it to exert force and to do work. This action, which is the converse of the former, is the principle of the dynamo ***used as a motor***. In the first case power is required to drive the armature; in the second, the armature rotating becomes a source of power. If we have the magnetic field, and supply power to drive the rotating conductor, we get the electric currents ; if we have the magnetic field and supply the electric currents to the conductor, it rotates and furnishes power. Whether the machine be used as generator or as motor, the magnetic field must be present: hence the fundamental consideration in theory is the theory of the magnetic field. As every dynamo will work (at least theoretically) either as generator or as motor, it should be possible to frame a general theory for any machine serving either of these two converse functions. For the sake of simplicity, however, these two functions will be separately considered in the present work.

The mathematical theory of the dynamo is, indeed, complex, and takes different forms for its expression in the various classes of machine now included under the one name of "dynamo." The progress of electromagnetic theory has simplified matters so much that it is possible to predict from the construction and dimensions of a dynamo its electrical output under given conditions of speed and load, and to design a machine to a given specification with certainty that when it has been built from those designs it will when set to work fulfil them with a very close degree of accuracy. In the present edition much more extended notice is given to ***dynamo design*** than was possible in the earlier editions. In the practice of design rules must be followed, most of which stand upon a true theoretical basis, but some are purely empirical and merely represent in convenient form the results of experience. In some cases algebraic formulæ are employed ; in other cases resort is had to graphic methods. Throughout the attempt is made to keep physical ideas, rather than abstract theories, well in view. The theory of the dynamo, then, which will be developed in the present work will not be a general mathematical theory. The aim will be to deal with physical[1] and experimental rather than mathematical ideas, though of necessity mathematical symbols must be used here as in every kind of engineering work.

Before, however, proceeding to the general theory of the dynamo, it will be expedient to introduce a few historical notes.

A few words may be said respecting some useful abbreviations used in describing machines. The initials AC, CC and DC, used respectively for *alternating-current, continuous-current* and *double-current*, need no explanation. The Author has adopted a convenient system for the notation of machines, in which the three principal numerical data—namely, the number of poles, the number of rated kilowatts (or in case of motors of horse-power), and the number of revolutions per minute—are set down after the initials that represent the style of the machine. Thus MP 10—500—85 means a multipolar generator of 10 poles, 500 kilowatts at 85 revolutions per minute; and A T B 30—600—200 means an alternator, three-phase, of B-type, having 30-poles, and rated at 600 kilowatts at 200 revolutions per minute.

---

[1] For Physical Theories see J. M. Gaugain, *Annales de Chimie et de Physique*, 1873; Antoine Breguet, *Annales de Chimie et de Physique*, 1879; Du Moncel, *Exposé des Applications de l'Électricité*, vol. ii.; Niaudet, *Machines Électriques*; Dredge's *Electric Illumination*; Schellen, *Die Magneto- und Dynamo-elektrischen Machinen* (3rd edition, 1883); and the author's *Cantor Lectures* delivered before the Society of Arts in 1882, which Lectures were the basis of the first edition of the present work.

CHAPTER II.

HISTORICAL NOTES.

Faraday's discovery of the magneto-electric induction of currents was made in the autumn of 1831, and communicated, on Nov. 24th, to the Royal Society in a paper printed in the *Philosophical Transactions*, and reprinted in the beginning of the first volume of Faraday's *Experimental Researches in Electricity.* His first experiments related to the production of induced currents in a coil by means of currents started or stopped in a neighbouring coil; from these he went on to currents generated in a coil moved in front of the poles of a powerful steel magnet. Upon thus obtaining electricity from magnets he attempted to construct "a new electrical machine." A disk of copper, 12 inches in diameter (Fig. 1) and about one-fifth of an inch in thickness, fixed upon a brass axle, was mounted in frames, so as to allow of revolution, its edge being at the same time introduced between the magnetic poles of a large compound permanent magnet, the poles being about half an inch apart.[1] The edge of the plate was well amalgamated, for the purpose of obtaining a good but movable contact, and a part round the axle was also prepared in a similar manner. Conducting strips of copper and lead, to serve as electric collectors, were prepared, so as to be placed in contact with the edge of the copper disk; one of these was held by hand to touch the edge of the disk between the magnet poles. The wires from a galvanometer were connected, the one to the collecting-strip, the other to the brass axle; then on revolving the disk a deflexion of the galvanometer was obtained, which was reversed in direction when the direction of the rotation was reversed.

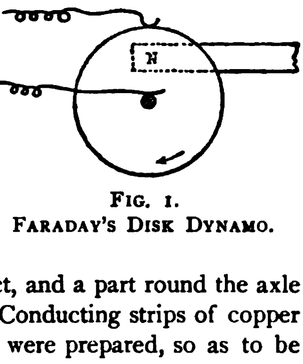


Fig. 1.
Faraday's Disk Dynamo.

[1] *Experimental Researches*, i. 25, art. 85. This piece of apparatus is still preserved at the *Royal Institution*. It was shown in action by the author of this work, at a lecture at the Royal Institution delivered April 11th, 1891.

"Here, therefore, was demonstrated the production of a permanent current of electricity by ordinary magnets." These effects were also obtained from electromagnets, and from copper helices without iron cores, the exciting current being separately provided by a battery. Several other forms of magneto-electric machines were tried by Faraday.

In one,[1] a flat ring of twelve inches external diameter, and one inch broad, was cut from a thick copper plate, and mounted to revolve between the poles of the magnet, two conductors being applied to make rubbing contact at the inner and outer edge at the part which passed between the magnetic poles. In another,[2] a disk of copper, one-fifth of an inch thick and only 1½ inch in diameter (Fig. 2), was amalgamated at the edge, and mounted on a copper axle. A square piece of sheet metal had a circular hole cut in it, into which the disk fitted loosely, a little mercury completed communication between the disk and its surrounding ring. The latter was connected by wire to a galvanometer; the other wire being connected from the instrument to the end of the axle. Upon rotating the disk in a horizontal plane, currents were obtained though the earth was the only magnet employed.

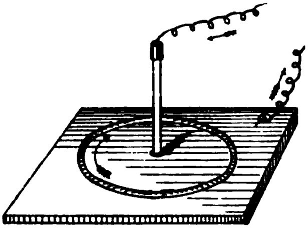


FIG. 2.—FARADAY'S TEETOTUM APPARATUS.

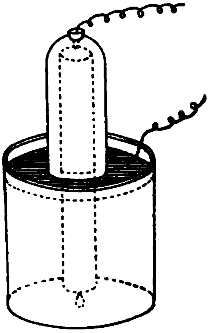


FIG. 3.—FARADAY'S ROTATING COPPER CYLINDER.

Faraday also proposed a multiple machine[3] having several disks, metallically connected alternately at edges and centres by means of mercury, which were then to be revolved alternately in opposite directions. In another apparatus[4] a copper cylinder (Fig. 3), closed at one extremity, was put over a magnet, one half of which it enclosed like a cap, and to which it was attached without making metallic

[1] *Experimental Researches*, i. art. 135.

[2] *Ib.*, art. 155.

[3] *Ib.*, art. 158.

[4] *Ib.*, art. 219.

contact. The arrangement was then floated upright in a narrow jar of mercury, so that the lower edge of the copper cap touched the fluid. On rotating the magnet and its attached cap, a current was sent through wires from the mercury to the top of the copper cap. In another apparatus,[1] still preserved at the Royal Institution, a cylindrical bar magnet, half immersed in mercury, was made to rotate, and generated a current, its own metal serving as a conductor. In another form,[2] the cylindrical magnet was rotated horizontally about its own axis, and was found to generate currents which flowed from the middle to the ends, or *vice versâ*, according to the rotation. In all these machines the operations were homopolar, and the induction continuous: but in another machine (Fig. 4) constructed some time later,[3] the operation was heteropolar, and the induction alternate. Here a simple rectangle of copper wire, attached to a frame, was rotated about a horizontal axis placed east and west, and generated alternate currents, which could be collected by a simple commutator.

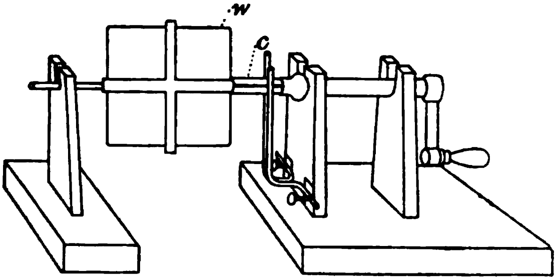


FIG. 4.—FARADAY'S ROTATING RECTANGLE.

Within a few months machines on the principle of magneto-induction had been devised by Dal Negro,[4] and by Pixii.[5] In the latter's apparatus a steel horseshoe magnet, with its poles upwards, was caused to rotate about a vertical shaft, inducing alternate currents in a pair of bobbins fixed above it, and provided with a horseshoe core of soft iron. Later, in 1832, Pixii produced, at the suggestion of Ampère,[6] a second machine, provided with commutators to rectify the alternating currents. Further improvements were made by Ritchie[1] and Watkins.[2] In 1833 appeared the machine of Saxton,[3] and two years later that of Clarke;[4] both having the steel horseshoe magnet a fixture, and having as a revolving armature an electromagnet consisting of a pair of bobbins wound upon a simple horseshoe of iron. Clarke's machine possessed many original details, including a special form of commutator for giving short, sharp currents for physiological purposes. In it the armature rotated, not opposite the ends, but in close proximity to the flat faces of the magnet. In Saxton's machine, which was shown to the British Association at Cambridge in 1833, the armature was rotated opposite the polar ends, and consisted of four coils. Von Ettingshausen,[5] in 1837, brought out a very similar alternate current machine, with a special device by which the alternate currents could be cut out. Poggendorff,[6] in 1838, devised a special mercury-cup commutator for Saxton's machines, to make the currents less discontinuous.

---

[1] *Experimental Researches*, i. art. 220.

[2] *Ib.*, art. 222.

[3] *Ib.*, iii. art. 3192.

[4] *Phil. Mag.* [3] i. 45, July 1832 (an oscillatory apparatus).

[5] *Ann. Chim. Phys.*, l. 322, 1832.

[6] *Ib.*, li. 76, 1832.

Other improvements in detail were made by Petrina,[7] who improved the commutator; Jacobi,[8] who pointed out the importance of using short cores for the armatures; Sturgeon,[9] who placed a shuttle-wound coil longitudinally between the limbs of a horseshoe magnet, and who also invented the simple two-part commutator or "unio-directive discharger," as he termed it; Stöhrer,[10] who showed how to construct a six-pole machine with six bobbins in the armature; Ritchie,[11] who employed tubular cores and a double winding; and Pulvermacher,[12] who in 1849 proposed the use of thin laminæ of iron as core-plates. In 1838, the Abbés Moigno and Raillard[13] proved that by taking a magneto-electric machine, the original magnet of which would support only a few grammes, and passing the electric current generated by it round a large electro-magnet, the latter could be made to support a weight of 600 kilogrammes. Magneto-electric machines, in which electro-magnets had been substituted for permanent magnets, had also been constructed by Page[1] of Washington, who also observed the important fact that an electromagnet excited by a magneto-electric machine became capable of effects greatly exceeding those of the original magnet. Woolrich,[2] in 1841, devised a multipolar machine for electroplating, having twice as many rotating coils as magnet-poles. These were employed at Birmingham for electro-plating, and marked at the time a distinct advance. Woolrich's plan of doubling the number of coils had the distinct advantage of rendering the current continuous instead of intermittent, one pair of coils being in full action at the moment when the other pair was at its dead point. Wheatstone[3] began his improvements in 1841, with a machine in which the armature coils were so grouped as to give a more completely continuous current. For this purpose five armatures, each consisting of a pair of short parallel cylindrical coils with iron cores, and each having a simple split-tube commutator, were arranged in a row along a single shaft, with six compound steel magnets between them, the five armatures being so set that they came successively into the position of greatest activity, no two of them being commuted at the same instant. They were connected in series with one another by wires, which joined the positive brush—a brass spring—of one to the negative brush of the next. Wheatstone[4] in 1845, Watt[5] in 1852, and Walenn[6] in 1862 patented the use of electromagnets instead of steel permanent magnets in such machines, such magnets being, of course, separately excited by a battery. In 1848 Jacob Brett[7] made the important suggestion of causing the current developed in the armature by the permanent magnetism of the field-magnets to be transmitted through a coil of wire surrounding the magnet, so as to increase its action.

---

[1] *Phil. Mag.* [3] viii. 455; [3] x. 280, 1837; and *Phil. Trans.*, ii. 318, 1833.

[2] *Ib.*, vii. 107, 1835.

[3] *Ib.*, ix. 360, 1836.

[4] *Ib.*, ix. 262, 1836; x. 365, 455, 1837; and Sturgeon's *Annals of Electricity*, i. 145.

[5] Gehler's *Physikalisches Wörterbuch*, ix. 122, 1838.

[6] *Pogg. Ann.*, xlv. 385, 1838.

[7] *Ib.*, lxiv. 58, 1845.

[8] *Ib.*, lxix. 194, 1846.

[9] *Annals of Electricity*, ii. 1, 1838. See also Sturgeon's *Scientific Researches*, p. 252; also *Phil. Mag.*, vii. 231, 1835.

[10] *Pogg. Ann.*, lxi. 417, 1884; lxxvii. 467, 1849.

[11] Specification of Patent, 14,899 of 1849.

[12] *Loc. cit.*

[13] Moigno's *Télégraphie Électrique*, 1849, p. 15.

In 1851, a new and important suggestion was put forward by Sinsteden.[8] Noting the circumstance that the induced current from a magneto-electric machine is able to excite an electromagnet up to a force more than double that of the permanent magnet in the machine, he remarks that this affords a means to augment the current up to an enormous degree. For if, starting with an exciting machine the magnet of which can lift 200 pounds, one uses the current from the revolving armature (built on Woolrich's plan with four coils) to excite an electro-magnet capable of lifting 500 pounds, then if one revolves opposite the poles of this electro-magnet, another armature of proportionately larger size, this latter armature will furnish currents at least double as strong. These may again be used to excite the electromagnets (large enough to sustain 1000 pounds) of a still larger machine. In this way, by using machines to excite one another in concatenation, one would obtain induction currents far exceeding in strength those of the most gigantic batteries hitherto known. These magneto-electric currents would, he remarks, be applicable to drive

---

[1] Silliman's Journal, xxxiv. p. 364, 1838, and xlviii. p. 393.

[2] Specification of Patent, 9431 of 1842; see also Shaw's *Manual of Electro-metallurgy*, 1845.

[3] Spec. of Patent, 9022 of 1841.

[4] Spec. of Patent, 10655 of 1845.

[5] Spec. of Patent, 834 of 1852.

[6] Spec. of Patent, 2772 of 1862.

[7] Spec. of Patent, 12054 of 1848.

[8] *Pogg. Ann.*, lxxxiv. 186, 1851. For Sinsteden's other researches see *Pogg. Ann.*, lxxvi. 29, 195 and 524, 1849; xcii. 1 and 220, 1854; xcvi. 353, 1855; cxxxvii. 290 and 483, 1869.

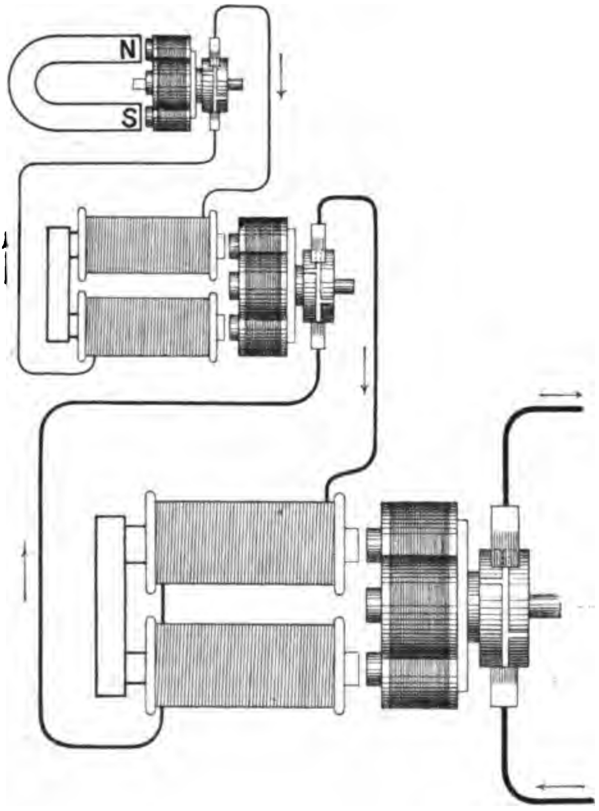


FIG. 5.—SINSTEDEN'S PLAN OF CONCATENATING MACHINES, 1851.

motors, and would have the advantage over battery currents that they cost nothing but the necessary driving power to maintain the rotation and occasion no consumption of zinc and acids. Sinsteden described experiments on the fusing of wires of copper and steel, and on glow lamps of platinum wire. He devised special forms of commutator, discussed the use of pole-pieces, the proper width of polar surfaces, self-excitation, and the lamination of the armature.

Nollet,[1] in 1849, devised an alternate-current machine, in the construction of which he was joined by Van Malderen; and after the death of Nollet this was developed, with the aid, first of Holmes, then of Masson and Du Moncel, into the "Alliance"[2] machine which, from the year 1863, did good service in the lighthouses of France. Holmes continued to perfect his work, and produced a fine machine,[3] which in 1857 received high commendation from Faraday. The great machine of Holmes shown in the International Exhibition of 1862, was a multipolar continuous-current machine, with a large commutator and rotating rollers for brushes; the bobbins, 160 in number, were arranged on the peripheries of two wheels, each about 9 feet in diameter. There were sixty horseshoe magnets arranged in three circles, each presenting radially forty poles. In 1867 Holmes remodelled his machine, making the field-magnets more powerful in proportion and leaving the induced currents uncommuted. This period was one of great activity. In 1855 Hjorth[4] patented a remarkable machine, having for its field-magnets a compound arrangement of permanent magnets to provide initial currents, and electromagnets to be excited up by the currents generated by the machine itself. This invention did not however come into any use. C. W. Siemens[5] in 1856 provisionally patented the famous shuttle-wound longitudinal armature, invented by Werner Siemens. In 1859,[6] he made the suggestion that the core only need rotate, the coils being fixed in grooves in the pole-pieces of the field-magnets; this being therefore a kind of "inductor alternator."

So far the whole of the inventions named have been permanent magnet machines, with the exception only of experimental forms, or machines requiring a battery to excite the magnetism. But with the years 1865 to 1867 the era of the commercial dynamo machine was entered upon. From 1863 onwards Mr. H. Wilde carried on a noteworthy series of researches, in the course of which he constructed the powerful generator which he described in a paper read before the Royal Society in April 1866.[1] The machine was described[2] by Brooke as follows:—"Wilde's magneto-electric machine. A machine of enormous and unprecedented power, arising from a happy combination of known facts and principles, has been constructed by Mr. Wilde for the purposes of illumination."[3] In this generator a Siemens' armature was caused to revolve between the poles of a large electro-magnet, which was excited by currents furnished by a small auxiliary armature revolving between small permanent magnets. Wilde carried the principle of concatenating machines one stage further. Starting with a small magneto to excite the electro-magnets of a larger machine, he applied the currents of this to excite the field-magnets of a third and still larger machine. Thus while the permanent magnets of the little exciter would only sustain a load of 40 pounds, the large electro-magnet of the third machine was estimated to sustain a load of 25 tons. The currents from the small armature were incapable of heating to redness thin iron wire, while those from the largest armature would fuse rods of iron and platinum, and produce a powerful arc light.[4]

---

[1] See Specification of Patent, 13,302 of 1850. See also Douglass in *Proc. Inst. Civil Engin.*, lvii. 1878–9.

[2] See Du Moncel's *Exposé des Applications de l'Électricité*, i. 361. Also see Le Roux, *Bulletin de la Société d'Encouragement*, 1868.

[3] See Douglas, *loc. cit.* Also Specifications of Patents, 573 of 1856, 2060 of 1868, and 1774 of 1869.

[4] Specifications of Patents, 12, 295 of 1848, 2198, 2199 of 1854, 806, 807 and 808 of 1855.

[5] Specification of Patent, 2017 of 1856. See W. Siemens, *Pogg. Ann.*, ci. 271, 1857.

[6] Specification of Patent, 512 of 1859.

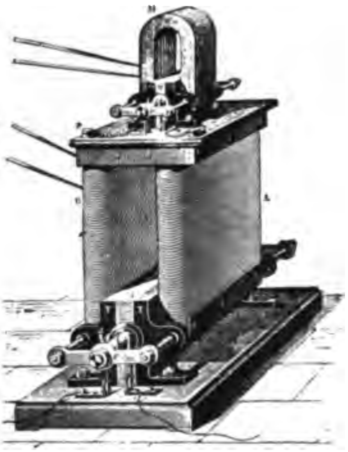


FIG. 6.
WILDE'S GENERATOR, 1866.

There is no doubt that the method of using a small machine to excite the magnets of a larger machine was in its time a very important invention.

---

[1] *Proc. Roy. Soc.*, xv. p. 107, 1866; and *Phil. Trans.*, clvii. 1867, p. 89. The machine was also exhibited at the Royal Society Soirée in March 1867.

[2] *Nat. Phil.*, p. 512, 1867.

[3] See also an article by Crookes on Wilde's magneto-electric machine in the *Quarterly Journal of Science*, October 1866, p. 503.

[4] See Grove, *Correlation of Physical Forces* (1874), p. 202.

In March 1867 Wilde invented and patented several multipolar alternating dynamo-electric machines, both self and separately excited. The self-excitation was effected by diverting through a commutator the currents induced in one or more of the armature bobbins. Both methods found wide acceptance in their commercial applications by him to the electro-deposition of metals from their solutions, to the electro-refining of copper, and to the production of the first search-lights of many of the battleships of the British Navy. Wilde's chief patents[1] embody the essential features of these and various subsequent developments.

In 1868 Wilde discovered a further property of the magneto-electric current to control and render synchronous the rotations of the armatures of a number of dynamo-electric and magneto-electric machines[2]: in fact he observed and announced that property of alternators to synchronise with one another which is made use of in the parallel-running adopted in every large generating station at the present time. Dr. Wilde's own account of his varied contributions to electrical engineering will be found in the *Journal* of the Institution of Electrical Engineers, vol. xxix. p. 3 (1899).

A quite different type of machine was suggested independently by Ritchie,[3] by Page,[4] and by Dujardin,[5] in which neither field-magnet nor armature rotated; the coils in which the currents were to be induced were wound upon polar extensions of the field-magnets, and the induction was produced by rotating in front of them pieces of soft iron, which set up rapid periodic variations in the magnetic field. Machines on this "inductor" principle were later devised by Henley, Wheatstone, Wilde, Holmes, Sawyer, by the author of this work, and then by Kingdon, Mordey, Stanley, Elihu Thomson, Dobrowolsky and many recent makers.

The principle of using the whole or part of the machine's own currents to excite the requisite magnetism of its field-magnets became gradually recognised. As mentioned above, Brett, Sinsteden, and Hjorth had all hinted at this principle. In 1858, Johnson,[6] patent agent for a foreign inventor, states, "It is proposed to employ the electromagnet in obtaining induced electricity, which supplies wholly or partially the electricity necessary for polarizing the electromagnets, which electricity would otherwise be required to be obtained from batteries or other known sources." In July 1866, Murray[1] stated that he had connected in series with the armature some coils wound on the field-magnets of his magneto machine, and recommended the adoption of this plan. In October 1866, Moses G. Farmer[2] of Connecticut wrote to Wilde describing his success in winding main circuit coils upon the field-magnets of his machine, so as to cause it to excite its own magnets. In November 1866, Baker[3] stated that the secondary currents from the revolving magnets might be applied to magnetize the fixed magnets. In December of the same year C. and S. A. Varley[4] filed a Provisional Specification for a machine having electromagnets only. Other machines were patented by the same inventors in June 1867, and another by O. and F. H. Varley in 1869. The electromagnets of the 1867 machine were wound with two separate circuits, supplied alternately with currents from two commutators which received the currents from two separate pairs of coils. Mr. S. A. Varley continued, in 1868 and 1871, to patent magneto-electric generators. In 1876 he returned to the self-exciting method, employing a multiple armature in which the principle was applied of cutting out each coil in succession during the rotation. In this machine also there were two windings on the field-magnets, one of greater resistance than the other, both of which were led to the lamp, the circuit of greater resistance being always closed. It was not, however, clear that this method of double winding was what is now understood as "compound winding,"[5] until such was laid down with legal authority by a Scotch judge fifteen years later. Returning to the self-exciting principle, we find that on January 17th, 1867, Dr. Werner Siemens[6] described to the Berlin Academy a machine for generating electric currents by the application of mechanical power, the currents being induced in the coils of a rotating armature by the action of electromagnets which were themselves excited by the currents so generated. In this machine also initial permanent magnetism was to be given by sending a preliminary current through the coils from a battery. To mark the significance of this departure from the then accepted types of magneto-electric machine, Siemens coined the term *dynamo-electrische Maschine* to describe his self-exciting machine, though the word does not appear in his paper of that date as printed. On the same day that this discovery was announced to the Royal Society, February 14th, 1867, a paper was read by Sir C. Wheatstone,[1] making an almost identical suggestion; but with this difference, that whilst Siemens proposed that the exciting coils should be in the main circuit, in series with the armature coils, Wheatstone proposed that they should be connected as a shunt. A self-exciting machine without permanent magnets had indeed been constructed for Wheatstone by Mr. Stroh in the summer of 1866. In 1867 Ladd[2] exhibited a self-exciting machine having two shuttle-wound armatures, a small one to excite the common field-magnet, a large one to supply currents for electric light. In accordance with the nomenclature introduced by Brooke, this became known as a *dynamo-magneto-electric machine.* (See footnote to p. 1 *supra.*)

---

[1] Specifications Nos. 516 and 3006 of 1863, 2762 of 1865, and 842 of 1867.

[2] *Phil. Mag.*, Jan. 1869; *Ann. Chim. Phys.*, xvi. 1869.

[3] *Phil. Mag.* [3] x. 280, 1837.

[4] *Annals of Electricity*, 489, 1839.

[5] *Comptes Rendus*, xviii. 837, 1844; xxi. 528, 892, 1881.

[6] Specification of Patent, 2670 of 1858.

---

[1] See *Engineer*, p. 42, July 20, 1866.

[2] *Proc. Lit. and Phil. Soc. of Manchester*, vi. 107.

[3] Specification of Patent, 3039 of 1866.

[4] Specification of Patent, 3394 of 1866. Other Varley Specifications are 1755 of 1867, 315 of 1868, 131 and 1150 of 1871, 4905 of 1876, 270 and 4435 of 1877, 4100 of 1878.

[5] See *Phil. Mag.* [4] xlv. 439, 1873.

[6] *Berliner Berichte*, Jan. 1867; *Proc. Roy. Soc.*, Feb. 14, 1867; Specification of Patent, 261 of 1867; and *Pogg. Ann.*, cxxx. 332, 1867.

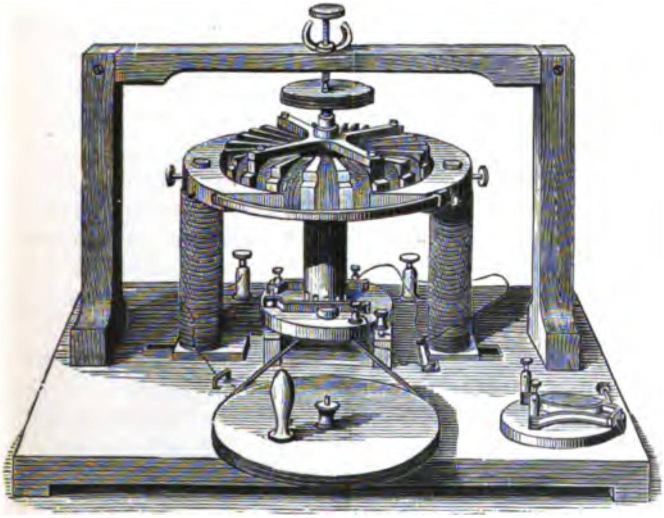


FIG. 7.—PACINOTTI'S MACHINE, WITH RING ARMATURE.

Meantime the question of procuring continuous currents, with less fluctuation in their strength, had come up, and had received from Pacinotti[3] an answer which, though it fell into temporary oblivion, is now recognised as of great merit. He devised a machine, first described in 1864, having as its armature an electromagnet in the form of a ring, the core consisting of a toothed iron wheel, between the teeth of which the coils were wound in sixteen separate sections. He denominated this a "transversal electromagnet." The coils being joined up in a closed circuit, if at any point a current was introduced, it flowed both ways through the coils to some other point where it was taken off by a return wire. By the device of leading down connections, at sixteen different points around the ring, to sixteen insulated pieces of metal arranged as a commutator, it was possible to cause magnetic poles to appear in the ring at any desired points. The principle of winding a continuous coil in separate symmetrical sections around a ring, or other figure of revolution, was independently invented, in 1870, by Gramme,[1] whose ring had no teeth, and was entirely overwound with wire. By winding an armature with a number of such symmetrically grouped coils which pass successively through the magnetic field, currents can be obtained that are practically steady. The introduction of the Gramme armature was at once recognised as marking an important step, and it gave a fresh impetus to invention. Innumerable forms have been given to the Gramme machine at different dates since its appearance in 1871, varying from small laboratory machines with permanent steel magnets, to large machines absorbing several hundred horse-power. Fig. 8 depicts the "A" Gramme of about 3 kilowatts, which came into the market. Those who desire more detailed information concerning the various patterns of Gramme dynamo should consult the earlier editions of this work, in which a number of forms[2] were described. They should also refer to the treatise of the late Alfred Niaudet, entitled *Machines électriques à courants continus, systèmes Gramme et congénères* (1881). Fig. 8 shows the ordinary "A" Gramme, the first pattern which came into commercial use, and of which, with little alteration of the design, many examples remain in use to-day. Its characteristic features are the ring-armature, made of an iron wire core entirely overwound with coils, and the double-circuit field-magnet having consequent poles above and below the armature. In 1873 von Hefner Alteneck[1] modified the longitudinal shuttle armature of Siemens by fashioning it as a drum covered with windings spaced out at symmetrical angles to secure the same advantage of continuity; and Lontin[2] in 1874 sought to perform a like transformation upon an armature with radiating poles.

---

[1] *Proc. Roy. Soc.*, Feb. 14, 1867. [2] *Phil. Mag.* [4] xxxiii. 544, 1867.

[3] *Nuovo Cimento*, xix. 378, 1865.

---

[1] *Comptes Rendus*, lxxiii. 175, 1871, and lxxv. 1497, 1872; and Specification of Patent, 1668 of 1870.

[2] Amongst these are the improved forms designed by M. Marcel Deprez, those designed by Mr. Hochhausen, and those made by the Fuller Company of New York; Mr. Wood, of New York, has also perfected the design in many details. Other modifications have been made by M. Raffard, by MM. Sautter Lemonnier and Co., and by other French engineers; of these, some account is given in *Industries*, Nov. 5th, 1886. For an account of Gramme's historical exhibit in the Paris Exposition of 1889, see *Industries*, vii. 285, 1889. Consult also the work entitled *Éclairage Électrique*, by H. Fontaine, upon the electric lighting of the Paris Exposition, published in 1890. A slow-speed machine of multipolar type, designed by Gramme in 1892, with flat-ring on the Schuckert plan, is described at p. 838 of the French edition of this book translated by M. Boistel.

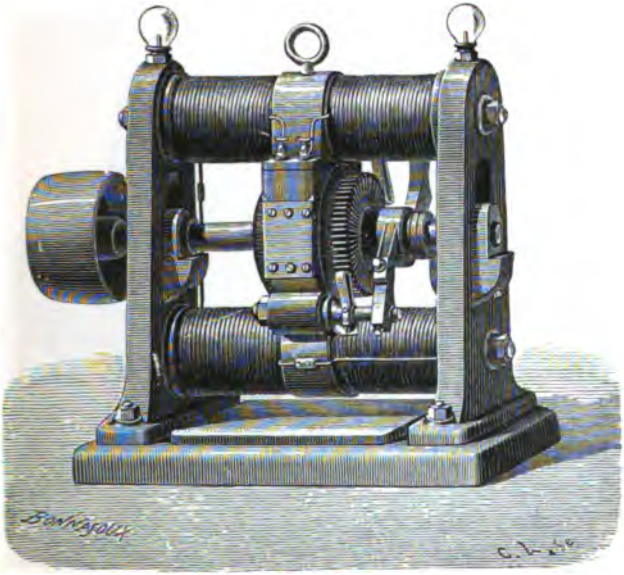


FIG. 8.—GRAMME DYNAMO, "A" PATTERN.

Siemens' dynamos originated with Messrs. Siemens and Halske, of Berlin, who manufactured many different forms. Some divergence developed itself between the types followed in Berlin and those produced by the London firm of Siemens Bros. Until about 1890 the characteristic feature of all forms was the drum-armature; but the largest Berlin machines have been made with rings. In some of the earlier patterns of Siemens' machines the cores of the drum were of wood, over-spun with iron wire circumferentially before receiving the longitudinal windings. In another of their machines there was a stationary iron core, outside which the hollow drum revolved; in other machines, again, there was no iron in the armature beyond the driving-spindle. The original horizontal pattern of Siemens' dynamo is depicted in Fig. 9. This was followed about 1880 by a vertical form. About the year 1882 various ways of compound-winding were tried,[1] in some of which the series and shunt-coils were wound on the same cores, and in others on different limbs, the usual practice being to wind the series-coils outside the shunt windings. Some large machines of his vertical pattern, including three 112-kilowatt compound-wound dynamos, were used at the Inventions Exhibition of 1885. In 1886 Messrs. Siemens and Halske, after trying some intermediate forms (depicted in former editions of this book), adopted for outputs of from 1 to 80 kilowatts the "over" type, with field-magnet consisting of a single massive casting. The commutators were of iron bars attached by screws at one end only, so as to be replaceable, and insulated by air-gaps. The London firm has constructed many large drum machines for central-station lighting, mainly of the "under"

---

[1] Specification of Patent, 2001 of 1873. A similar suggestion had been thrown out the previous year by Worms de Romilly.

[2] Specification of Patents, 473 of 1175, 386 and 3264 of 1876.

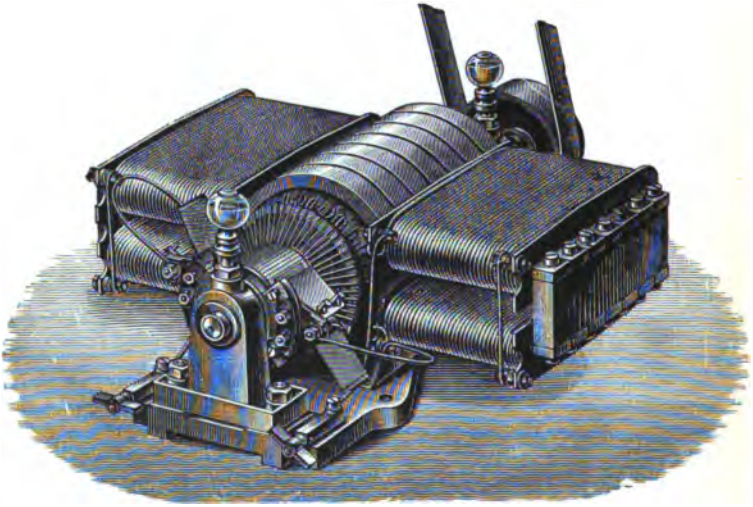


Fig. 9.—SIEMENS' DYNAMO WITH VON HEFNER ALTENECK'S DRUM-WOUND ARMATURE.

---

[1] See series of papers in the *Elektrotechnische Zeitschrift*, March-June, 1885, by Dr. O. Frölich.

type. Fig. 10 represents one of these machines, compound-wound, with the series winding on one limb only. At the Naval Exhibition of 1891 were shown three fine dynamos of 180 kilowatts each, at the slow speed of 350 revolutions per minute. The armature was 24 inches in diameter, 36 inches long, and weighed 2·4 tons; the entire dynamo weighed 13·6 tons. The armature conductors were stranded bars; the commutator of hard-drawn copper, insulated with mica, with 144 segments, 9 inches long, with three pairs of brushes to collect the 1500 amperes. The rocker is provided with worm-wheel to adjust the proper lead. There are two independent circuits of 72 turns each, which are put in parallel with one another by the brushes, which are made broad enough to overlap three consecutive bars of the commutator.

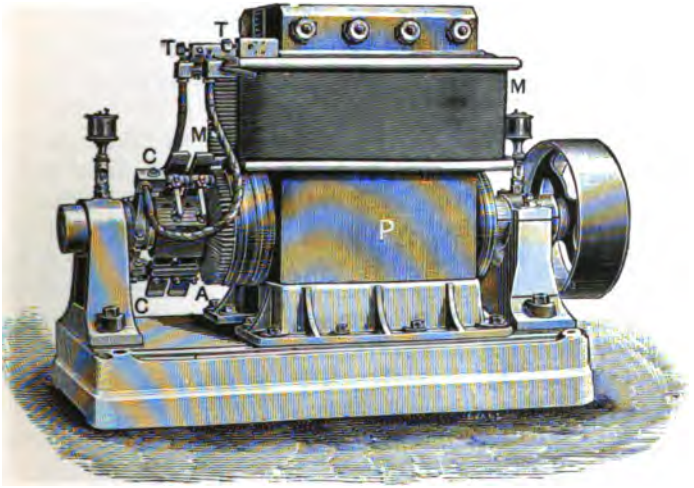


FIG. 10.—SIEMENS' DYNAMO (London type of 1890).

Towards the end of 1886 a form of multipolar ring machine, with ring external to the field-magnets, was brought out almost simultaneously by Messrs. Ganz of Buda-Pesth, Messrs. Fein of Stuttgart, and by Messrs. Siemens and Halske of Berlin.[1] It will be sufficient to describe the machines of the latter firm.

The field-magnet is stationary and internal to the ring. In the small machines this consists of a substantial cross-shaped mass of cast iron, through the centre of which passes the driving-shaft. The four poles, after receiving the exciting coils, are furnished with polar expansions, which approach close to the inside of the ring. The ring core is made up of thin iron washers bolted together, and is overhung, being supported on one side by a brass spider keyed to the shaft. The advantages of this type are the ease of repair, the immense cooling surface of the armature, and the non-necessity of applying binding-wires. In the larger machines the brushes are applied against the exterior of the ring itself, with the result that the most noticeable feature of the machine is the enormous commutator and the huge star-shaped brush-holder which supports the various sets of brushes (see Plate XXV.) In the central stations of Berlin and other German cities these large dynamos are combined with huge engines of the marine type, the whole having a very imposing appearance.

---

[1] For further information about the various machines of this type see *Elektrotechnische Zeitschrift* for April and May, 1887; *La Lumière Électrique*, xxiv. 182, 1887; *Centralblatt für Elektrotechnik*, ix. 186, 410, and 581, 1887, and the Official Report of the Frankfort Exhibition of 1891.

At the Paris Exhibition of 1900 Messrs. Siemens Bros. showed a 16-pole 1570 kilowatt machine running at 200 revolutions per minute.

Gramme and Siemens both devised many special forms of machines, some furnishing alternating currents,[1] others continuous currents. The alternate-current generators required, of course, to have their field-magnets separately excited by means of continuous currents from an auxiliary 'exciter.' Bertin in 1875, Brush in 1879, and Siemens,[2] in 1880, revived the method of shunt-winding.

In 1878 Pacinotti[3] devised a kind of armature in which the conductors took the form of a flat disk or fly-wheel. About the same time Schuckert, of Nürnberg, began to manufacture a modified Gramme machine, having a discoidally flattened ring armature, into which the magnetic lines entered flank-wise. A very similar type was independently developed by Gülcher. Brush[4] also introduced his famous dynamo embodying the principle of open-coil working. He also introduced the simultaneous use of a shunt and a series winding for the purpose of enabling the machine to do either a large or small amount of work, without causing too great a variation of voltage. Another open-coil machine was introduced in 1880 by Elihu Thomson and E. J. Houston,[5] of Philadelphia. About the same time Weston[6] devised several forms of dynamo, and in particular developed shunt-wound machines having drum armatures with toothed core-disks. Many other American inventors produced dynamos, amongst them Edison,[1] who began in 1878, with a machine in which the motion was oscillatory instead of rotatory, a device which had been tried by Dujardin[2] in 1856, by Siemens[3] in 1859, by Wilde[4] in 1861, and abandoned. Edison himself abandoned it in 1879 for a form of machine having a modified Hefner-Alteneck armature and an elongated shunt-wound electromagnet. With the assistance of Mr. Upton, he designed the bipolar machine depicted in former editions of this work. It had a Siemens's drum-armature rotating between heavy pole-pieces excited by a very long magnet with tall columnar limbs. An Edison 60-light machine of this older pattern, tested by the Committee of the Munich Exhibition, was found to give an electrical efficiency exceeding 87 per cent.; but its commercial efficiency was only 58·7 per cent. This was due to the production of wasteful eddy-currents in the bolts which held together the armature and in other masses of metal. Edison's large "Jumbo" steam dynamos were even less efficient, and required a fan to be attached to the armature shaft to keep them cool by a forced draught of air.

---

[1] Specification of Patents, Gramme, 953 of 1878 ; Siemens, 3134 of 1878.

[2] *Phil. Trans.*, March 1810.

[3] *Nuovo Cimento* [3] i.1881.

[4] Specification of Patent, 2003 of 1878.

[5] Specification of Patent, 315 of 1880.

[6] Specifications of Patents, 4280 of 1876, 1614 and 2194 of 1882.

The field-magnets of all the larger machines turned out by Edison prior to 1884 had a number of long iron columns as cores to receive the coils. After that date, in consequence of the researches of Dr. John Hopkinson, the more compact arrangement of a single magnetic circuit with short stout magnets was adopted by the Edison companies on both sides of the Atlantic. The 1888 type of bipolar Edison dynamo, as used in the States, is depicted in Fig. 11. These field-magnets are of cast iron, with a massive yoke, and stand upon a high footstep of zinc to diminish short-circuiting through the bedplate. These machines are shunt-wound, and are intended for incandescent lighting work. The bearings are longer and the mechanical arrangements in every way superior to those of the older machines. At the Paris Exhibition of 1889 were a number of these bipolar dynamos built by the Edison Machine Company, of Schenectady, ranging from a small 2½-kilowatt machine, 30 inches high, to one of 150 kilowatts, 8½ feet high. Drawings of these machines were given in earlier editions of this book.

---

[1] Specifications of Patents, 4226 of 1878, 2402 of 1879, 1240 and 2954 of 1881, and 2052 of 1882.

[2] See Du Moncel's *Exposé des Applications*, i. p. 372.

[3] Specification of Patent, 512 of 1859.

[4] Specification of Patent, 924 of 1861.

Though this type has been obsolete since 1895, it was exceedingly successful, being of excellent mechanical construction.

Returning to the year 1881, the Paris Exhibition marked great progress in electrical engineering in general. The same year saw a revival of alternate-current machines in the forms devised by Lord Kelvin [1] (and independently by Ferranti) and Gordon,[2] the latter of whom constructed large two-phase generators.

About this time multipolar dynamos began to come into favour, the multipolar drum armature introduced by Lord Elphinstone [3] and Mr. Vincent, and the multipolar ring, independently, by Schuckert, Gramme, Gülcher, and Mordey.[4] Lord Elphinstone in particular drew attention to the importance of perfecting the magnetic circuit, though, for purely mechanical reasons, his machine soon became obsolete. Hopkinson [5] showed how greatly the performance of a dynamo was improved by shortening and making more compact its magnetic circuit; whilst Crompton,[6] amidst a number of improvements in detail, showed the advantage of increasing the cross-section of iron in the armature core. He brought the smooth-core armature to a

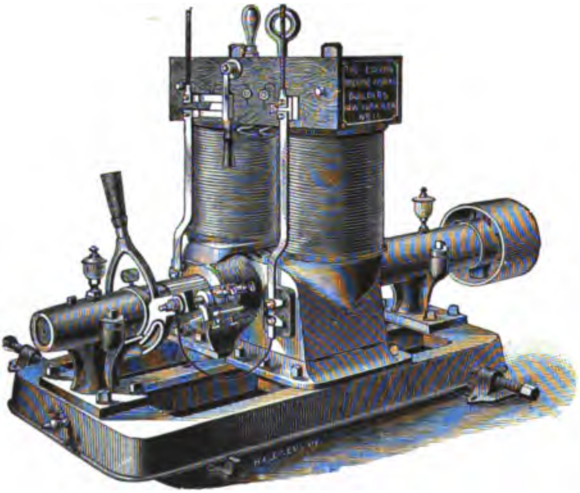


FIG. 11.—EDISON DYNAMO (1888 Type).

---

[1] Specification of Patent, 5668 of 1881.

[2] Specifications of Patents, 5536 of 1881 and 2871 of 1882.

[3] Specifications of Patents, 332 of 1879, and 2893 of 1880.

[4] Specification of Patent, 400 of 1883.

[5] Specification of Patent, 973 of 1883.

[6] Specifications of Patents, 2618 and 4810 of 1882, and 4302 of 1884.

high pitch of perfection. A complete account of Mr. Crompton's successive stages of improvements[1] would occupy a volume in itself. Besides the improvements made in conjunction with Mr. Kapp on general design, and more favourable use of iron in the armature, a number were made in conjunction with Mr. Swinburne on various modes of winding, and on machines with conductors embedded in the core-disks. He adopted driving-horns of delta-metal or aluminium bronze, fitted into the substance of the laminated core. Then came the production of imbricated and compressed stranded conductors to obviate eddy-currents; and lastly, the adoption of multipolar series windings for drum-armatures. With large 4-pole machines for central-station lighting Messrs. R. E. Crompton and Co. had great success. The construction of some of their armatures was described in earlier editions of this work.

Notable amongst the engineers who contributed to progress in dynamo design in the years from 1880 to 1890, were the brothers J. and E. Hopkinson, Mr. W. M. Mordey, Mr. Gisbert Kapp, Mr. C. E. L. Brown. The theoretical researches of Dr. John Hopkinson, his introduction of the conception of the characteristic curve, and his rational method of calculation of magnetic circuits, are dealt with elsewhere. The firm of Mather and Platt, who constructed dynamos on the designs of the Hopkinsons, brought out not only the modified Edison-Hopkinson dynamo, but also the "Manchester" dynamo, a modified Gramme machine. Dr. J. Hopkinson improved the original bipolar Edison machine by making the magnetic circuit more compact, and by reconstructing the armature with cores of larger section and better mechanical construction. In the older construction, the bolts and their attached end-pieces furnished a circuit in which idle currents were constantly running wastefully round, with consequent heating and loss. Dr. Hopkinson also introduced the improvement of winding the magnets with a copper wire of square section, wrapped in insulating tape. The wire packs more closely round the iron cores than an ordinary round wire.

A remarkably complete account of one of these dynamos, constructed by Messrs. Mather and Platt, was published in 1886.[2] As

---

[1] See remarks by Mr. Crompton in *Proc. Inst. Civil Engineers*, lxxxiii. 125, 1885; *Journal Soc. Teleg. Engineers*, xv. 546, 1886; and *Journal Inst. Elec. Engineers*, xix. 239, 1890, and xx. 308, 1891.

[2] See paper on *Dynamo-electric Machinery*, by Drs. J. and E. Hopkinson, in the *Philosophical Transactions* for 1886, Part I. This most valuable paper was reprinted in the *Electrician*, xviii. 39, 63, 86 and 175, in issues of Nov. 19th and 26th, and Dec. 3rd and 31st, 1886, where the figures of the plates are printed in the text. It is reprinted in Dr. Hopkinson's *Original Papers*, vol. i. p. 84.

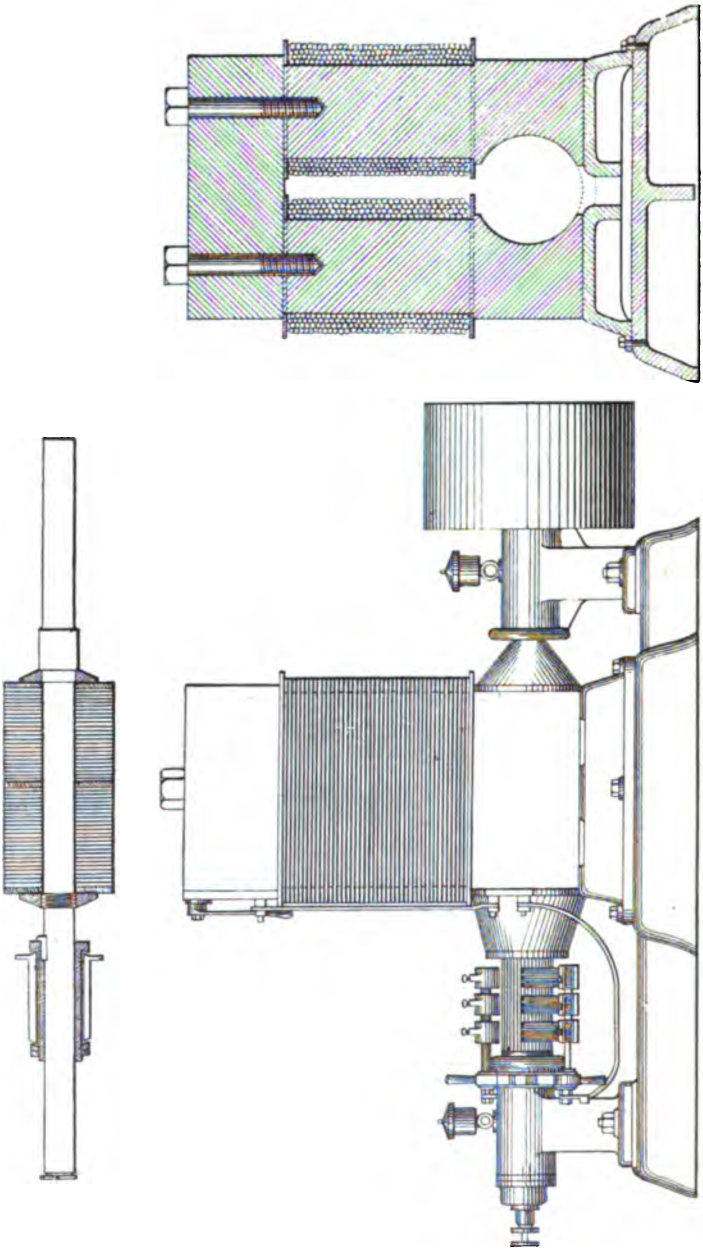


Fig. 12.—Edison-Hopkinson Dynamo: Elevation, Section, and Section of Armature

this machine is often referred to, a detailed account of it is important. Its design may be gathered from Fig. 12.

The machine described is intended for a normal output of 320 amperes at a pressure of 105 volts, running at 750 revolutions per minute. The field-magnet consists of two limbs connected by a yoke of rectangular section. Each limb, together with its pole-piece, is formed of a single forging. The wrought iron used for these and the yoke is of annealed hammered scrap; the magnetic properties being those described in Chapter IV. The section of the limbs is nearly rectangular, with rounded corners. The yoke is bolted to the limbs, the joints being well surfaced. The bed-plate is of iron, a zinc base 12·7 cm. high being interposed. The armature core is built up of about 1000 thin plates of soft wrought iron, insulated from the shaft, and separated by paper from one another. They are held between two end-plates, one of which is secured by a washer shrunk on the shaft, and the other by a screw-nut and lock-nut.

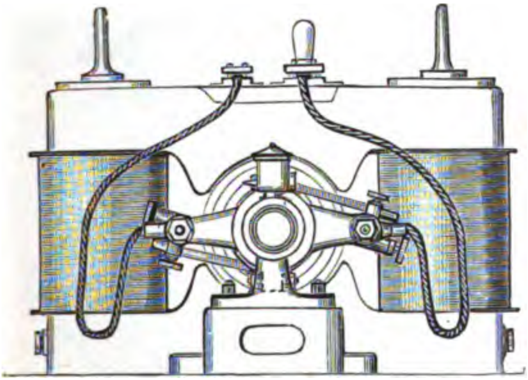


FIG. 13.—"MANCHESTER" DYNAMO (End Elevation).

The following are the dimensions of the iron parts:—Diameter of armature core, 24·4 cm.; of internal hole, 7·62 cm.; of shaft, 6·98 cm.; length of core 50·8 cm. Length of field-magnet limb, 45·7 cm.; breadth, 22·1 cm.; width (parallel to shaft), 44·45 cm. Length of yoke, 61·6 cm.; width, 48·3 cm.; depth, 23·2 cm. Diameter of bore of field-magnets, 27·5 cm.; depth of pole-piece, 25·4 cm.; width (parallel to shaft), 48·3 cm.; width between pole-pieces, 12·7 cm. Area of section of iron in armature core, 810 sq. cm. Angle subtended by bored face of pole-pieces, 129°. Actual area of pole-piece, 1513 sq. cm., effective area, 1600 sq. cm. Thickness of gap space, 1·5 cm. Area of section of limbs, 980 sq. cm.; ditto of yoke, 1120 sq. cm.

The windings are as follows: Magnetizing coils, 11 layers on each limb of copper wire, 2·413 mm. diameter. Total convolutions, 3260; total length, 4570 metres. Armature, 50 convolutions in two layers of 20 convolutions of stranded copper wire, consisting of 16 strands of wire 1·753 mm. diameter. Resistance (at 13·5° C.): field-magnet, 16·93 ohms; armature, 0·0009947 ohm. Normal magnetizing current, 6 amperes. Commutator, 40 copper bars insulated with mica. The machine had a commercial efficiency over 93 per cent.

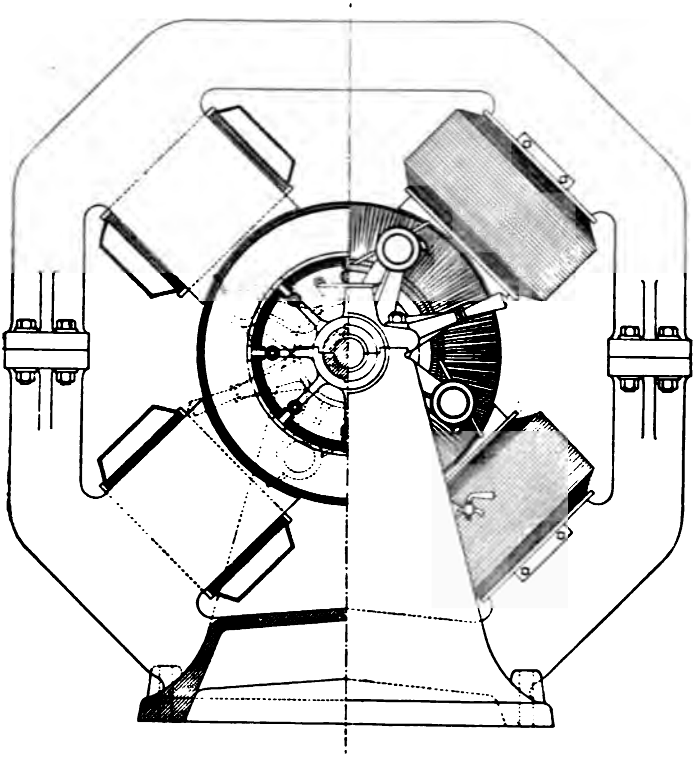


FIG. 14.—BROWN'S 4-POLE DYNAMO (OERLIKON CO., 1889). END VIEW. (Scale 1 : 24.)

Fig. 13 depicts the "Manchester" dynamo, designed by Dr. E. Hopkinson. Its compact field-magnet had wrought-iron cores with massive cast-iron yokes.

Mordey's dynamos were manufactured by the Brush Electrical Engineering Company, the makers of the Brush arc-lighting machine. The development by Mr. Mordey of the "Victoria" machine, a

4-pole flat-ring machine, from the original Schuckert machine commenced with the discovery (by the aid of his method of examining the distribution of potentials round collectors), that by reducing the size of the pole-pieces to make space for a 4-pole field, the electrical output was doubled, without increase of speed, when using the same ring as employed by Schuckert with a two-pole field. The pole-pieces

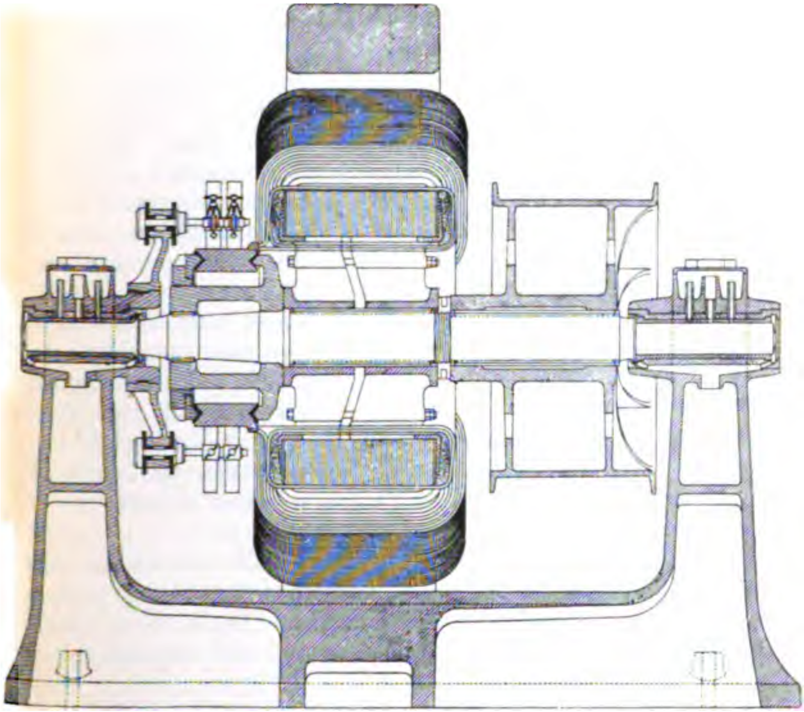


FIG. 14*a*.—BROWN'S 4-POLE DYNAMO. LONGITUDINAL SECTION.

in the earlier Schuckert machines consisted of hollow iron shoes or cases which occupied a large angular breadth along the circumference of the ring. The Mordey-Victoria machine had a narrower form of pole-piece, not covering more than 35° of angular breadth of the circumference of the armature. The pole-pieces were of cast iron shrunk upon the cylindrical cores of soft wrought iron which received the coils. The armature was built up of charcoal iron tape, coiled upon a strong foundation ring, contact between successive layers being prevented by coiling paper between. Illustrations of these machines were given in earlier editions of this book.

Mr. C. E. L. Brown, as chief electrical constructor of the Oerlikon Works down to 1892, introduced many admirable engineering features into the construction of continuous-current machines, beside all the pioneering work which he subsequently achieved in alternate-current engineering. In the former editions of this work a Plate was given of a massive bipolar machine having an armature with closed slots, designed by Mr. Brown. Figs. 14 and 14*a* depict a historical type, two of them being shown at the Paris Exhibition of 1889, transmitting 240 H.P., one working as generator, the other as motor. Their admirable construction won great attention at the time. They stood nearly 8 feet high, and when running at 500 revolutions per minute delivered 270 amperes at 625 volts. They were ring-wound, with smooth core-disks; resistance, brush to brush, 0·025 ohm; commutator, 200 parts. Field-magnet coils in series with armature were each wound with 60 turns of 1 mm., copper sheet 30 cm. in width. Weights were as follows:—Frame and magnet cores 11,600 kilos, armature iron 1430, armature copper 132, armature complete 2420, magnet copper 1370. Total weight of complete machine, 15,700 kilos, or nearly 16 tons. Commercial efficiency at full load 93–94 per cent. With Brown originated the vertical-shaft pattern of dynamo adapted to be driven by a water turbine, the method of barrel-winding of armatures, and a host of other features now in general use.

Simultaneously with these improvements in the continuous-current dynamo, developments of no less importance were taking place in the design and construction of alternators. The achievements of Ferranti, Mordey, Ganz, Brown, Dobrowolsky and Westinghouse in particular claim attention.

Mordey introduced a notable departure in the use of the single compact magnetic circuit with branching poles, thus favouring the use of a revolving field-magnet. Brown carried the development one stage further by the introduction of the imbricated pattern of field magnets. To Brown and the Oerlikon Company, to Dobrowolsky and the Allgemeine Electricitäts-Gesellschaft of Berlin, and later to Brown, Boveri and Company, are due a list of improvements in the methods of armature construction. Ganz and Co. were early in the field with alternators constructed entirely of laminated iron in both field-magnet and armature cores; while Zipernowsky devised for the Ganz Company a method of compounding the alternators. The advantage gained in large machines by the fly-wheel action of the heavy revolving masses has told in favour of this type, though practice has reverted to the use of magnet wheels with radial poles, each pole being separately wound. Polyphase alternate-current generators have been introduced, chiefly since 1891, for the purpose of furnishing two or more alternate currents differing in phase from one another; the reason for these machines being the convenience of distributing power by alternate currents to polyphase motors. At one time the "inductor" type of alternator, having no copper in the moving parts, appeared to be preferred: but since 1900 few such have been made. The "umbrella" type of dynamo, with vertical driving shaft, was introduced by Brown for turbine service, and has been used in many very large machines. The largest of this type in use are the two-phase alternators at Niagara, constructed by the Westinghouse Co., chiefly from the designs of George Forbes. The Exhibition of Frankfurt in 1891 marked the serious introduction of polyphase methods for the transmission of power. The Paris Exhibition of 1900 was chiefly notable for the disappearance of the bipolar continuous-current machine, and for a remarkable development of large alternators of high voltage. Disk armatures, which were introduced by Desroziers and by Fritsche, have become obsolete. Special methods of construction to facilitate the sparkless collection of large currents have been devised by Ryan, W. B. Sayers, Mordey, Fischer-Hinnen, and Déri.

The theory of the dynamo dates back to the investigations of Weber[1] and of Neumann[2] respecting the general laws of magneto-electric induction, followed by Jacobi's[3] calculations and experiments respecting the performance of an electric motor, by Poggendorff's[4] and Koosen's[5] investigations of the theory of the Saxton magneto-machine, and by the researches of Lenz,[6] Joule,[7] Le Roux,[8] and of Sinsteden.[9] These researches were followed at a long interval by those of Favre,[10] followed by silence for twenty years, broken only by the pregnant, but almost totally forgotten, little paper in which Clerk-Maxwell[1] laid down a theory for self-exciting machines. On the revival of electric lighting the theory of the dynamo was again studied, important contributions being made by Mascart,[2] Hagenbach,[3] von Waltenhofen,[4] Hopkinson,[5] Herwig,[6] Meyer and Auerbach,[7] and Joubert. The latter founded the modern theory of alternate-current machines. Hopkinson[9] devised the method of representing, by a curve, the relation between the current and the working electromotive-force of the machine; such curves, under the name of "characteristics," subsequently formed the basis of the theoretical researches of Marcel Deprez.[10] In 1880 Frölich[11] began a series of investigations, both experimental and theoretical, that led to equations of remarkable simplicity, if not of more than approximate value, and in 1883 Clausius,[12] adopting Frölich's fundamental expression for the law of the electromagnet, evolved with great elaboration a theory in which all the various secondary effects arising in generators were taken into account—a theory which he later extended to the case of motors.

---

[1] *Elektrodynamische Maasbestimmungen* (1846).

[2] *Berliner Berichte*, p. 1, 1845; and p. 1, 1847.

[3] *Pogg. Ann.*, li. 370, 1840; lxix. 181, 1846; and *Krönig's Journal*, iii. 377, 1851. Also *Ann. Chim. Phys.* [3] xxxiv. 451, 1852.

[4] *Pogg. Ann.*, xlv. 390, 1838.

[5] *Pogg. Ann.*, lxxxv. 226; and lxxxvii. 386, 1852.

[6] *Pogg. Ann.*, xxxi. 483, 1834; xxxiv. 385, 1835; and xcii. 128, 1854.

[7] *Annals of Electricity*, iv. v. 1839–40; *Phil. Mag.* [3] xxiii. 263, 347 and 435, 1843.

[8] *Ann. Chim. Phys.* [3] l. 463, 1857.

[9] *Pogg. Ann.*, lxxxiv. 181, 1851.

[10] *Comptes Rendus*, xxxiv. 342, 1853; xxxix. 1212, 1854; xlvi. 337, 658, 1858.

Theoretical considerations led Marcel Deprez[13] in 1881, to the conclusion that a dynamo driven at a certain critical speed ought to generate currents at a constant potential if its field-magnets were provided with a second coil to furnish from a battery or other source an independent and constant auxiliary excitation. Perry suggested the more general solution of introducing into the circuit of a separately excited or magneto machine, a series dynamo also driven at a constant speed, to give the additional volts needed at full load, to compensate for the drop of voltage which would otherwise take place. This was almost immediately followed by the general adoption of the so-called *compound winding*, for the purpose of obtaining a self-regulating dynamo, this advance being the subject of conflicting rival claims.[1] The term compound winding is due to Messrs. Crompton and Kapp.

---

[1] *Proc. Royal Soc.*, Mar. 14, 1867; and *Phil. Mag.* [4] xxxiii. [474] 1867.

[2] *Journal de Physique*, vi. 204, 297, 1877; and vii. 89, 1878.

[3] *Archives des Sciences Physiques*, lv. 225, March 1876; and *Pogg. Ann.*, clviii. 599, 1876.

[4] *Wiener Berichte*, lxxx. 601, 1879.

[5] *Proc. Inst. Mech. Engineers*, 238, 1879; and 266, 1880.

[6] *Wied. Ann.*, viii. 494, 1880.

[7] *Wied. Ann.*, viii. 494, 1879.

[8] *Ann. de l'École Normale*, x. 131, 1881; and *Journal de Physique* [2] ii. 293, 1883.

[9] *Proc. Inst. Mech. Engineers*, 238, 1879.

[10] *Comptes Rendus*, xcii. 1152, 1881; and *La Lumière Électrique*, xv. 1, 1885.

[11] *Berl. Berichte*, 962, 1880; *Electrotechnische Zeitschrift*, ii. 134, 170, 1881; vi. 128, etc., 1885; and ix., Nov. 1888.

[12] *Wied. Ann.*, xv. 353, 1883; xxi. 385, 1884; *Phil. Mag.* [5] xvii. 49 and 119, 1884.

[13] *La Lumière Électrique*, December 8, 1881, and January 5, 1884.

The other branch of the subject, that of the electric motor, goes back to the discovery by Faraday[2] in 1821 of electromagnetic rotation, and the invention, in 1823, by Barlow[3] of his rotating wheel. The earliest electric motors in which the principle of attraction by an electromagnet was applied were those of Henry,[4] in 1831, and of Dal Negro,[5] in 1832, and these were followed in 1833 and 1834 by the motors of Ritchie[6] and of Jacobi,[7] and in 1837 by that of Davenport.[8] Many other inventors devised machines of this kind, some of the most famous being Page[9] in the United States, Davidson[10] in Scotland, Wheatstone[11] in England, Froment[12] in France, and Pacinotti[13] in Italy. The discovery that the action of a dynamo is the simple converse of that of the motor, and that the same machine can serve either function, appears to have been made by Lenz[1] in 1838. It was known to Jacobi[2] in 1850, though it only came into general recognition somewhat later. It was certainly known in 1852, for in the fourth edition of Davis's *Magnetism*, published at Boston, an apparatus, described as a "revolving electromagnet" (a slight modification of Ritchie's motor) is shown, on page 212 as a motor, and the same apparatus is again shown on page 268 as a generator, accompanied by the remark that "any of the electromagnetic instruments in which motion is produced by the mutual action between a galvanic current and a steel magnet may be made to afford a magneto-electric current by producing the motion mechanically." Walenn[3] explicitly stated the same point in 1860; and it was also stated by Pacinotti in 1864. The principle of transmitting power from one dynamo used as a generator to another used as a motor is claimed for Fontaine and Gramme, as a discovery made in 1873, when such an arrangement was shown at Vienna. It has been noisily claimed, but without the shadow of reason, for Marcel Deprez,[4] who did not, however, discover it until 1881. In 1882 Ayrton and Perry made the important discovery of the automatic regulation of motors, to run with constant velocity, by methods akin to, but the converse of, those adapted for making dynamos self-regulating. Since that date, the improvements made in continuous current motors, though great, have been in mechanical perfection of design and detail. The alternate-current dynamo with its separately excited field-magnet does not make a convenient alternate-current motor, as it is not self-starting. When once started, however, it runs in absolute synchronism with the generator. Hopkinson, who apparently was not aware of the prior researches of Wilde, dating from 1869, announced the synchronous control of alternators as a deduction from theory in 1883.

---

[1] The invention of the "series and shunt" winding is claimed for several rivals. Brush undoubtedly first used it commercially, but whether with any knowledge of all its advantages is doubtful. It has also been claimed by Mr. S. A. Varley on the strength of the machine described in his patent specification, No. 4905 of 1876, in which there were two circuits, of different resistance, both having coils wound on the field-magnets, and both going to the lamp. He has obtained a decision in the law courts that this strange arrangement anticipated that described by Brush. Compound winding was, however, described in 1871 by Sinsteden, in *Pogg. Annalen* (*Supplement-Band*, v.), 651. It was mentioned as having some advantages by Sir C. W. Siemens in *Philosophical Transactions*, March 1880. It is also claimed for Lauckert (see note by M. Boistel, page 100 of his translation of first edition of this work); Paget Higgs (*Electrical Review*, xi. 280, and *Electrician*, Dec. 23, 1882); J. W. Swan, see Bosanquet (*ib.*, Dec. 9, 1882); J. Swinburne (*ib.*, Dec. 23, 1882); S. Schuckert (*ib.*, Oct. 13, 1883). It is claimed in America by Edison; and it has been patented by Messrs. Crompton and Kapp (*ib.*, June 9, 1883). See also Hospitalier (*L'Électricien*, No. 20, 1882). Students should also consult a series of articles in *The Electrician*, vol. x., beginning Dec. 16, 1882, by Mr. Gisbert Kapp. Further, they should see a paper by Dr. Louis Bell in the *Electrical World*, xvi. 383, 1891.

[2] Journal of *Royal Institution*, September 1821.

[3] Barlow, *On Magnetic Attraction* (1823), 279; and *Encyclopædia Metropolitana* (1824), iv. art. *Electromagnetism*, 36.

[4] *Silliman's Journal*, xx. 340, 1831. Also Henry, *Scientific Writings* (1886), i. 54. [5] *Annali delle Scienze Lombardo-Veneto*, March 1834.

[6] *Phil. Trans.*, 1833 [2], 318. [7] *L'Institut*, lxxxii. Dec. 1834.

[8] See *Annals of Electricity*, ii. 1838; *Encyclopædia Britannica*, (ed. vii.) art. *Voltaic Electricity*, 687.

[9] *Silliman's Journal*, xxxiii. 1838; and [2] x. 344 and 473, 1850.

[10] *Mechanics' Magazine*, xxxviii. 240, 1843.

[11] Specification of Patent, 9022 of 1841.

[12] See *Cosmos*, x. 495, 1857, and *La Lumière Électrique*, ix. 193, June 1883.

[13] *Nuovo Cimento*, xix. 378, 1865.

Baily, in 1879, showed how to produce rotation by the currents induced in a copper disk placed in a systematically shifting magnetic field. Ferraris, in 1888, made the important suggestion to drive a motor by two independent alternate currents of similar period, but differing in phase, thus producing a rotatory magnetic field. The same suggestion came independently from Nikola Tesla, who first put such motors into practical form. Dolivo-Dobrowolsky independently suggested the use of three circuits, not independent of one another, but mutually connected; which system came into vogue under the name of *Drehstrom* or *Three-Phase* about the year 1890. Motors for use in two-phase or three-phase circuits may be either synchronous or asynchronous, according as to whether they have an independently excited field-magnet, or whether instead they have a mere "rotor" receiving its currents by induction. Many forms of rotatory-field motors have since been devised by various engineers. Dolivo-Dobrowolsky and C. E. L. Brown in particular brought the induction motor to a remarkable pitch of perfection. In the States a two-phase motor on a different plan was perfected by Stanley and Kelly. The success of these polyphase motors, in which the rotating part is an entirely independent simple structure of iron and copper, receiving its currents by induction and without any commutator or circuit connexions, has led to the device of single phase induction motors for use with simple alternate currents. The structure of these motors resembles that of the polyphase motors, since the revolving part receives its currents solely by induction.

---

[1] See Sturgeon's *Annals of Electricity*, iii. 384, 1838; and *Pogg. Ann.*, xxxi. 483, 1838.

[2] *Mémoire sur la Théorie des Machines électromagnétiques.*

[3] Specification of Patent, 2587 of 1860.

[4] Specification of Patent, 2830 of 1882. See *Jour. Soc. Telegr. Engineers*, xii. 301, 1883.

In 1886 John and Edward Hopkinson[1] published a remarkable paper, developing, from theoretical considerations respecting the induction of magnetism in a magnetic circuit of given form and materials, a theory of the dynamo, the perfection of which may be judged by the fact that its use, as now extended by various workers, enables the performance of a machine to be predicted with extraordinary accuracy from the design as laid down in the working drawings. Other contributions to the theory of dynamos have been made by Lord Kelvin[2] (windings to secure maximum efficiency), Kapp[3] (pre-determination of characteristic curve), Rücker[4] (limits of self-regulation), Esson[5] (design of multipolar machines), and others. Hering,[6] Fritsche,[7] and Arnold[8] have published studies on the modes of winding armatures; and the latter has given a formula for all kinds of continuous-current machines with closed-coil armatures. Methods of analyzing the various losses of energy due to friction, hysteresis and eddy-currents have been devised by Mordey,[1] and later by Kapp[2] and Housman,[3] independently. The theory of alternate current motors both of the asynchronous and of the synchronous types has of late received much attention from various writers. The reader is referred to the author's book *Polyphase Electric Currents* (2nd edition, 1900), to Steinmetz's *Alternating Current Phenomena* (3rd edition, 1900), or to *Behrend's Induction Motor* (1901).

---

[1] *Phil. Trans.*, i. 331, 1886.

[2] *Journal de Physique*, (2) ii. 240, 1887; and *Comptes Rendus*, xciii. 474, 1881.

[3] *Journ. Soc. Telegr. Engineers*, xv. 518, 1887.

[4] *Phil. Mag.*, (5) xix. 462, June 1885.

[5] *Journal Inst. Electrical Engineers*, xx. 1891.

[6] Hering's *Principles of Dynamo-electric Machines*, New York, 1889.

[7] Fritsche's *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[8] Arnold's *Die Ankerwickelung der Gleichstrom-Dynamomaschinen*, Berlin, 1891; 3rd edition, 1899.

A vast amount of attention has been paid to the question of the commutation of the current in continuous current generators, and the suppression of sparks at the commutator. See the various studies of Thomas,[4] Reid,[5] Hawkins,[6] Fischer-Hinnen,[7] Arnold,[8] Kapp,[9] Parshall,[10] and Hobart.[11]

The most recent problem under discussion generally has been the driving and excitation of large alternators when they are to be coupled in parallel. For a statement of the problem, and discussion thereof, the reader is referred to the papers of Leblanc.

The methods to be adopted in dynamo design, and the right apportioning of the various inevitable losses of energy has been recently discussed by Parshall,[12] Rothert,[13] Hobart,[14] Mavor,[15] Esson,[16] Scott,[17] and others. The latest treatise on continuous current generators is that of Arnold, *Die Gleichstrom Maschine*, Berlin, 1902.

---

[1] *Journal Inst. Electrical Engineers*, xviii. 620, 1889.

[2] *Electrician*, xxvi. 700, 1891.

[3] *Ib.*; see also *Journal Inst. Electrical Engineers*, xx. 303, 1891.

[4] *Electrician*, xl. 557, Feb. 18, 1898.

[5] *Trans. Amer. Inst. Elec. Engineers*, Dec. 15, 1897.

[6] *Electrician*, xxxix. 13 et seqq., 1897.

[7] *Elektrotechnische Zeitschrift*, xix. 850, Dec. 1898.

[8] *Ib.*, xx. 5 and 97, 1899. [9] *Ib.*, xx. 32. 1899.

[10] *Electric Generators*, London, 1900.

[11] *Journ. Inst. Elec. Engineers*, xxxi. 170, Sept. 1901.

[12] *Electrician*, xlvi. 170, Nov. 1900.

[13] *Elektrotechnische Zeitschrift*, xxiv. 405, May 1903. [14] *Op. citat.*

[15] *Journ. Inst. Elec. Engineers*, xxxi. 218, 1901; and xxxii. 473, 1902.

[16] *Ib.* xxxii. 329, Jan. 1903.

[17] *Ib.* xxxii. 362, Jan. 1903.

CHAPTER III.

PHYSICAL THEORY OF DYNAMO-ELECTRIC MACHINES.

ALL dynamos are based upon the discovery made by Faraday in 1831, that electric currents are generated in conductors by moving them in a magnetic field. Faraday's principle may be enunciated as follows:—When a conductor is moved in a magnetic field so as to cut the lines of force, there is an electromotive-force induced in the conductor, in a direction at right angles to the direction of the motion, and at right angles also to the direction of the lines of force.

Dr. Fleming has given a most useful rule for remembering this connexion between motion, magnetism and induced electromotive-force. Hold the thumb and the first and middle fingers of the right hand as nearly as possible at right angles to each other, as in Fig. 15, so as to represent three rectangular axes in space. If the thumb point in the direction of the motion, and the forefinger point along the direction of the magnetic lines, then the middle finger will point in the direction of the induced electromotive-force.[1]

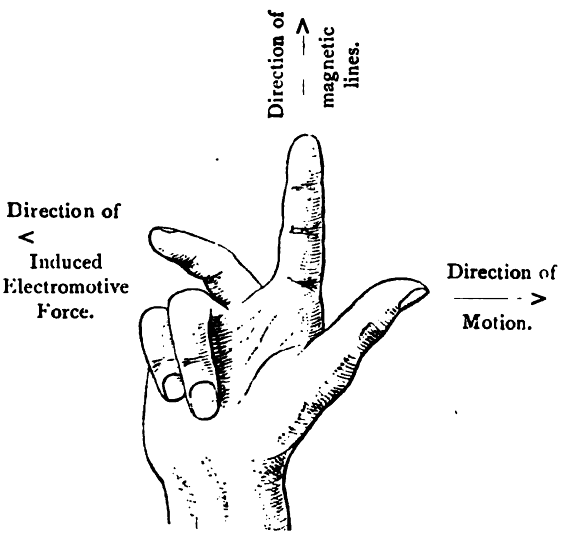
This induced electromotive-force is, as Faraday showed, proportional to the number[2] of magnetic lines cut per second; and is, therefore, proportional to the density of the magnetic field, and to the length and velocity[1] of the moving conductor. For steady currents, the flow of electricity in the conductor is, by Ohm's well-known law, directly proportional to this electromotive-force, and inversely proportional to the resistance of the conductor. For sudden currents, or currents whose strength is varying rapidly, this is no longer true. And it is most important in the construction of dynamo-electric machinery, to bear in mind that the "resistance" of a coil of wire, or of a circuit, is by no means the only obstacle offered to the generation of a momentary current in that coil or circuit; but that there are reactive electromotive-forces due to the "self-induction" exercised by one part of a coil or circuit upon another part or parts of the same. Indeed in many cases of currents changing suddenly or with high frequency the reactance is quite is important as, and in some cases more

---

[1] A more usual rule for remembering the direction of the induced currents is the following adaptation from Ampère's well known rule:—Supposing a figure swimming in any conductor to turn so as to look along the (positive direction of the) lines of force. Then if he and the conductor be moved towards his right hand, he will be swimming with the current induced by this motion.

Another right-hand rule is this:—Put the thumb at right angles to the fingers in the plane of the palm of the hand. Imagine the magnetic lines of the field to be entering the front of the palm normally, and that the hand is then moved in the direction of the thumb. The index finger will then point in the direction of the induced electromotive-force.

[2] For the numerical signification to be attached to the term "number of magnetic lines," see p. 72.



Right Hand.

FIG. 15.—ILLUSTRATION OF FLEMING'S RULE.

---

[1] If the direction of the motion is not at right angles to the direction of the field, the resolved part of the velocity in the direction at right angles to the field must be considered as the effective velocity.

important than, the resistance. Into the reactance there also enters in the possible effect due to any capacity (such as that of a condenser) in the circuit.

To understand clearly Faraday's principle—that is to say, how it is that the act of moving a wire so as to cut magnetic lines of force can induce or generate a current of electricity in that wire—let us inquire what a current of electricity is.

A wire through which a current of electricity is flowing looks in no way different from any other wire. No man has ever yet seen the electricity running along in a wire, or knows precisely what is happening there. Indeed, it is still a disputed point which way the electricity flows, or whether or not there are two currents flowing simultaneously in opposite directions. One thing is certain ; that the energy does not flow along the substance of the wire at all, but is transmitted across the surrounding medium, transversely. Until we know with absolute certainty what electricity is, we cannot expect to know precisely what a current of electrity is. But no electrician is in any doubt as to one most vital matter, namely, that when that which is called an electric current

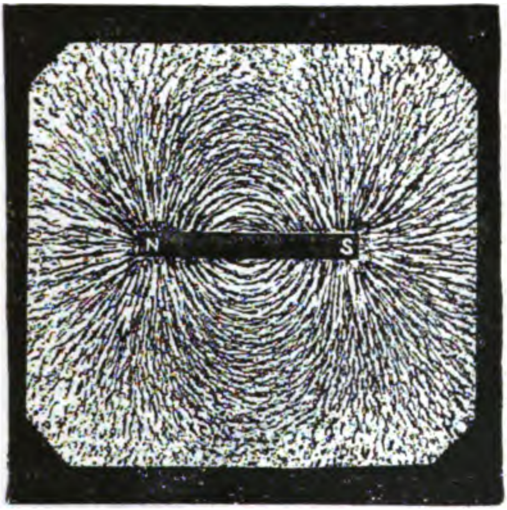


FIG. 16.—MAGNETIC FIELD OF BAR-MAGNET.

flows through a wire, the magnetic forces with which that wire is thereby, for the time, endowed, and which are proportional in intensity to it, reside not in the wire itself, but in the space surrounding it. Everyone knows that in the space or "field" surrounding a magnet there are magnetic forces whose direction and intensity are conveniently portrayed by magnetic "lines of force." These lines start in tufts from the N-pointing pole and curve round to the S-pointing pole of the magnet. They are invisible until, by dusting iron filings into the field, their presence is made known, though they are always in reality there (Fig. 16), and can be detected in several independent ways. A view of the magnetic field at the pole of a bar magnet, as seen end-on, would, of course, exhibit merely radial lines, as seen in Fig. 17.

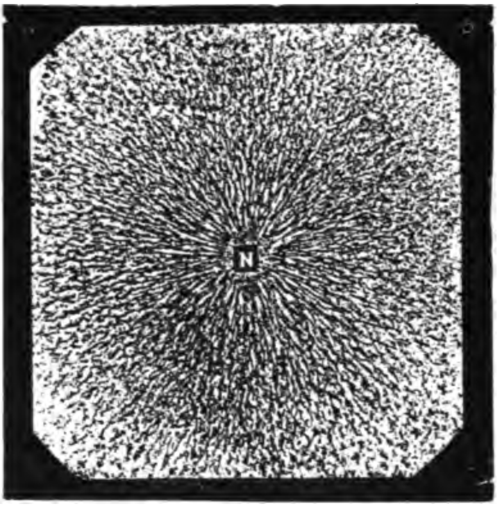


FIG. 17.—MAGNETIC FIELD ROUND ONE POLE, END-ON.

Now, every electric current (so called) is surrounded by a magnetic field, the lines of which can be similarly revealed. To observe them, a hole is bored through a card or a piece of glass, and the wire which carries the current must be passed up through the hole. When iron filings are dusted into the field they assume the form of concentric circles (Fig. 18) showing that the lines of force run completely round the wire, and do not stand out in tufts. In fact, every conducting wire is surrounded by a sort of magnetic whirl, like that shown in Fig. 19. A great part of the energy of the so-called electric current in the wire consists in these external magnetic whirls. To set them up requires an expenditure of energy. They grow and spread out into space from the wire as from a central core. The current on being started does not instantly assume its full strength, part of the energy being employed during the variable period in building up this surrounding field. On stopping the current by breaking the circuit this surrounding energy returns back into the circuit; the field, as it collapses upon the wire, tending to maintain the current, and causing the spark seen at the break of the circuit. It is these magnetic whirls which act on magnets, and cause them to set, as galvanometer needles do, at right angles to the conducting wire.

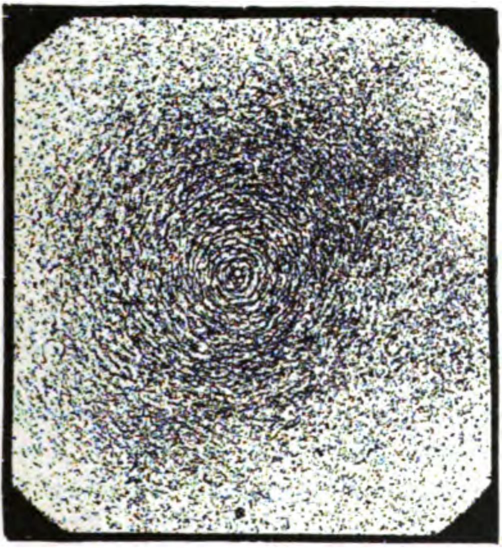


FIG. 18.—MAGNETIC FIELD SURROUNDING CURRENT.
THE CONDUCTING WIRE SEEN END-ON.

Now, Faraday's principle of induction is nothing more or less than this :—That by moving a wire near a magnet, across a space in which there are magnetic lines, the motion of the wire, as it cuts across those magnetic lines, sets up magnetic whirls round the moving wire, or, in other language, generates a so-called current of electricity in that wire. Poking a magnet pole into a loop or circuit of wire also necessarily generates a momentary current in the wire loop, because it momentarily sets up magnetic whirls. In Faraday's language, this action increases the number of magnetic lines embraced by the circuit.

It is, however, necessary that the moving conductor should, in its motion, so cut the magnetic field as to alter the number of magnetic lines that pass through the circuit of which the moving conductor forms part. Without a variation in the magnetic flux that penetrates the circuit there will be no induction. And induction will always occur in any circuit when any change in the flux takes place, however that change may be produced.

If the magnetic field be not a uniform one, then the effect of taking the coil by a simple motion of translation from a place where the lines of force are dense to a place where they are less dense, will be to generate currents. Or, if the motion be to a place where the lines of force run in the reverse direction, the effect will be the same, but even more powerful.

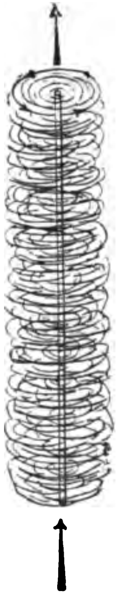


FIG. 19. MAGNETIC WHIRL SURROUNDING WIRE CARRYING CURRENT.

In the process called *homopolar* or "unipolar" induction (Chap. XXIII.), conductors with sliding contacts move continuously through a uniform field ; there being no reversals.

We may now summarise the points under consideration and some of their immediate consequences, in the following manner :—

(1) To induce currents in a conductor there must be

relative motion between conductor and magnet, of such a kind as to alter the number of the magnetic lines embraced in or enclosed by the circuit.

(2) Increase in the number of magnetic lines embraced by the circuit generates an electromotive-force in the opposite sense to that induced by a decrease.

(3) The more powerful the magnet pole or magnetic field, the higher will be the electromotive-force generated.

(4) The more rapid the motion, the higher will be the electromotive-force.

(5) By joining in series a number of such moving conductors, the electromotive-forces in the separate parts are added together; hence very high electromotive-forces can be obtained by using numerous coils properly connected in series.

(6) Since the quantity or strength of the current depends on the resistance of the conductors in the circuit, as well as on the electromotive-force, all unnecessary resistance should be avoided.

(7) The number of magnetic lines being finite, the process of a generating machine in alternately increasing and diminishing the flux enclosed by the moving conductor must necessarily generate currents alternate in direction.

(8) By using a suitable commutator, all the currents, direct or inverse, induced during recession or approach, can be turned into the same direction in the wire that goes to supply currents to the external circuits; and if the rotating coils are properly grouped so that before the electromotive-force in one set has died down another set is coming into action, then it will be possible, by using an appropriate commutator, to combine their separate currents into one current which is continuous and practically uniform.

(9) As induction depends upon the relative motion of conductor and magnetic lines, it is a mere question of mechanical convenience whether the magnet be stationary while the copper conductor moves, or whether the conductor is fixed while the magnet moves.

(10) To the conductor which is generating the electro-

motive-force by cutting the magnetic lines, it makes no difference what the origin of those lines is, whether from a permanent magnet of steel or from an electromagnet, provided the number of magnetic lines so cut is the same. All dynamo-electric machines are in this sense magneto-electric.

(11) To the moving conductor it makes no difference what the origin of the motion is. Whether the motion be due to a steam-engine, or to a gas-engine, or to hand-driving, or to driving by means of an electric current in the wire itself (as in the case of electric motors), it makes no difference to the moving conductor, which, provided the speed and the number of magnetic lines to be cut are given, will generate the same electromotive-force.

We will next examine some fundamental points in the general mechanism and design of dynamo machines for continuous currents. We will begin with the various organs or parts of the machine. Having discussed these, we take up the nature of the processes that go on in the machine when it is at work, the action of the magnetic field on the rotating armature, and the reactions of the armature upon the field in which it rotates. We shall then consider the properties of the material with which we are concerned, including the conductivity of copper, the resistance of insulating materials, and the magnetic properties of iron so far as is needed for the purpose of dynamo design.

ORGANS OF CONTINUOUS-CURRENT DYNAMOS.

The simplest conceivable dynamo is that sketched in Fig. 20, consisting of a single rectangular loop of wire rotating in a simple and uniform magnetic field between the poles of a large magnet. If the loop be placed at first in the vertical plane, the number of lines that pass through it from right to left will be a maximum, and as it is turned into the horizontal position the number diminishes to zero; but on continuing the rotation the lines begin again to penetrate the loop from the opposite side, so that there is a negative maximum when the loop has been turned through 180°. During the half-revolution, therefore, currents will have been induced in the loop, and these currents will be in the direction from back to front in the part of the loop which is rising on the left, and in the opposite direction, namely, from front to back, in that part which is descending on the right. On passing the 180° position, there will begin an induction in the first sense, for now the number of negative lines of force is diminishing, which is equivalent to a positive increase in the number of lines of force: and this increase would go on until the loop reached its original position, having made one complete turn. If, then, to each end of the loop there were separately attached a metal collar on the shaft, and on each collar there pressed a spring, wires connected to these springs would convey an *alternating current* to the circuit. If, however, it is desired to adapt the apparatus to furnish a continuous current, a special adjunct must be added.

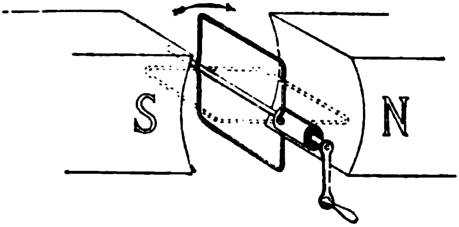


FIG. 20.—IDEAL SIMPLE DYNAMO.

Seeing then that in all cases the rotation of an armature between the poles of a magnet generates alternating currents, if we would commute these alternately-directed currents into one direction in the external circuit, we must add a *commutator*. In its most primitive form the commutator consisted of a metal tube slit into two parts, and mounted on a cylinder of hard wood or other suitable insulating material; each half being connected to one end of the loop, as indicated in Fig. 20. Against this commutator press a couple of metallic springs or "brushes" (Fig. 21), which lead away the currents to the main circuit. It is obvious that if the brushes are so set that the one part of the split tube slides out of contact, and the other part slides into contact with the brush, at the moment when the loop passes through the positions when the induction reverses itself, the alternate currents induced in the loop will be "rectified" or "commuted" into one direction. We should expect, therefore, the brushes to be set so that the commutation shall take place exactly as the loop passes through the vertical position. In practice, however, it is found that a slight *forward lead* must be given to the brushes, for reasons which will presently appear. In Fig. 22 are shown the brushes B B′, displaced so as to touch the commutator not exactly at the highest and lowest points, but at points displaced in the direction of the line D D, which is called the "diameter of commutation." The argument is in no wise changed if for the single ideal loop we substitute, as proposed by Sturgeon in 1835, the simple rectangular coil represented in Fig. 23, consisting of many

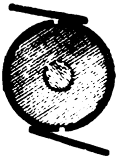


FIG. 21.—TWO-PART COMMUTATOR.

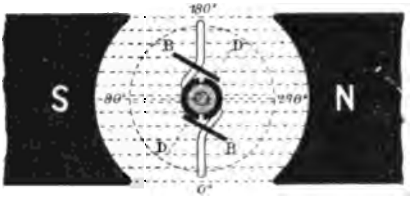


FIG. 22. SIMPLE LOOP IN SIMPLE FIELD.

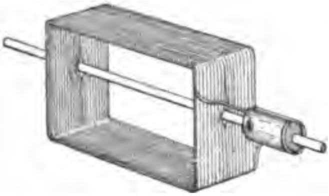


FIG. 23. SIMPLE RECTANGULAR COIL.

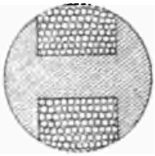


FIG. 24.—SECTION OF OLD SHUTTLE-WOUND SIEMENS ARMATURE.

turns of wire, in each of which a simultaneous inductive action is going on, making the total induced electromotive-force proportionately greater. This form, with the addition of an iron core, is, indeed, the form given to armatures in 1856 by Siemens, whose shuttle-wound armature is represented in section in Fig. 24. A small magneto-electric machine of the old pattern, having the shuttle-wound armature, is shown in Fig. 25. Though this form has long been abandoned, save for small motors, telephone ringers, and automobile igniters, it gave a great impetus to the machines of its day; but for all large work it has been entirely superseded by the ring armatures and drum armatures presently to be described.

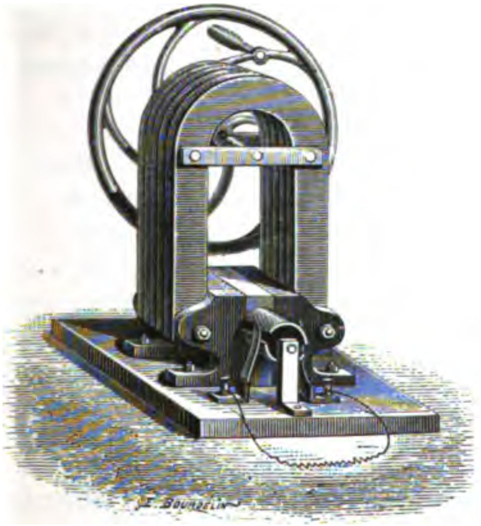


FIG. 25.—OLD SIEMENS MACHINE, WITH SHUTTLE-WOUND ARMATURE AND PERMANENT MAGNETS.

We have seen that the dynamo in its simplest form consists of two main portions: (1) an *armature*, which in revolving induces electromotive forces in the copper conductor wound upon it; (2) a *field-magnet*, that is to say a magnet whose function is to provide a field of magnetic lines, to be cut by the armature conductors as they revolve. In all dynamos, whether for continuous currents or for alternate currents, these two parts can be recognised. In almost all continuous-current machines the field-magnet stands still, and consists of a comparatively simple and massive electromagnet; whilst the armature, which is a more complex structure, is the portion which rotates. In alternate-current machines the field-magnet is usually multipolar, and in the majority of modern cases rotates whilst the armature is stationary; nevertheless there are many alternators of old patterns and small size in which the armature rotates and the field-magnet stands still. The criterion as to which portion is properly called "field-magnet," and which "armature," is not the question of rotation or otherwise. The name of *field-magnet* is properly given to that part which, whether stationary or revolving, maintains its magnetism steady during the revolution; and the name *armature* is properly given to that part which, whether revolving or fixed, has its magnetism changed in a regularly repeated fashion when the machine is in motion. In a generator the armature is that part which is connected in circuit with the distributing mains and gives current to them. In a motor the armature is that part which receives the currents from the mains. It is now customary to classify dynamos under two types: A-*type*, those with stationary magnets and revolving armature; B-*type*, those with stationary armature and revolving magnet-wheel. There is a third type amongst alternators, known as the *Inductor-type*, in which the magnetising coils as well as the armature stand still, the only revolving part being a set of inductors or polar masses of iron. In the case of continuous-current machines there is another feature of primary importance, namely, the apparatus for collecting the currents from the revolving armature. This apparatus consists of two essential parts; the *commutator* (or *collector*) attached to the armature and revolving with it, and the *brushes*. The latter, which are conducting contact pieces of carbon or copper held pressed against the surface of the rotating commutator, are provided with special *brush-holders* mounted upon an adjustable frame or *rocker*.

In the case of alternate-current machines there is no need of a commutator; but, in general, these machines have to be provided with some device for making a sliding connexion. For in those of the A-type the armature coils must be brought into continuous metallic relation with the conductors of the main circuit; and in those of the B-type there must still be sliding contacts to maintain the coils of the revolving magnet wheel in continuous metallic connexion with the auxiliary exciting circuit. In either case the appropriate device consists of a pair of *slip-rings*, against each of which a *brush* presses.

In addition to the electrical and magnetic features enumerated above, there are certain purely mechanical features which need to be considered. The revolving part must be mounted on an appropriate *shaft*, the design of which is a matter of mechanical engineering. Upon the shaft the revolving armature is carried by means of a *hub* or *spider* which supports the *core-disks*. These are almost invariably *slotted* at the periphery to receive the copper conductors in *slots* between projecting *teeth*; though occasionally smooth cores are still found having a *surface winding* secured in its place by *binding-wires* and propelled by projecting *driving-horns*. The shaft itself must be supported in suitable *bearings*, and be provided with *lubricators* to secure cool running, To receive the power from the engine a *pulley* must be provided, unless the dynamo is to be driven direct by a *coupling* from an engine mounted on the same bed-plate. Lastly, the whole dynamo must be erected upon an appropriate *bed-plate*, which in some cases is placed upon *rails*, so that it may be shifted from time to time by the aid of tightening screws, as the belt grows slack.

ARMATURES.

Returning to the ideal simple loop, we may exhibit it in its relation to the 2-part commutator somewhat more clearly by referring to Fig. 26. The same split-tube or 2-part commutator will suffice if a loop of two or more turns be substituted, as shown in Fig. 27, for the single turn.

But we may substitute also for the one loop a small coil consisting of several turns wound upon an iron ring. This coil (Fig. 28), which may be considered as one section of a Pacinotti or Gramme ring, will be penetrated by magnetic lines as the loop was. In the position drawn, it occupies the highest point of its path, and the flux of magnetic lines through it will be a maximum. As it turns, the number of lines that penetrate it will diminish, and become zero when it is at 90° from its original position. But a little consideration of its action will suffice to show that if another coil be placed at the opposite side of the ring it will be performing an exactly similar inductive action at the same moment, and may therefore be connected to the same commutator. If these two coils are united in parallel, as shown in Fig. 29, the joint electromotive-force will be the same as that due to either separately; but the resistance offered to the current by the two jointly is

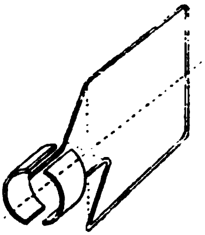


FIG. 26.
SIMPLE LOOP ARMATURE.

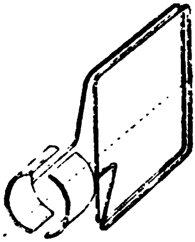


FIG. 27.
LOOP ARMATURE OF TWO TURNS.

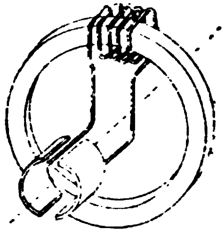


FIG. 28.
SIMPLE RING ARMATURE WITH ONE COIL.

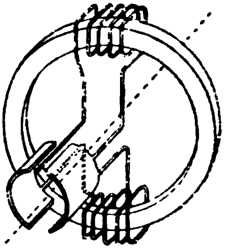


FIG. 29.—SIMPLE RING ARMATURE WITH TWO COILS IN PARALLEL.

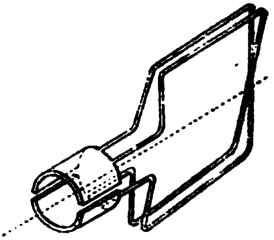


FIG. 30.—SIMPLE LOOP ARMATURE WITH TWO COILS IN PARALLEL.

half that of either. It is evident that we may connect two parallel loops in a similar fashion to one simple 2-part collector. If the two loops are of one turn each, we shall have the arrangement sketched in Fig. 30 ; but the method of connecting is equally good for loops consisting of many turns each.

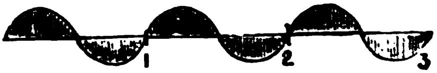


FIG. 31.—SIMPLE CURVE OF SINES, REPRESENTING AN ALTERNATING OR UNDULATORY CURRENT.

Now, with all these arrangements involving the use of a 2-part commutator, whether there be one circuit only or two circuits in parallel in the coils attached thereto, there is the disadvantage that the currents, though commutated into one direction, are not absolutely continuous. In any single coil without a commutator there would be generated, in successive revolutions, currents whose variations may be graphically expressed by a recurring sinusoidal curve, such as Fig. 31.

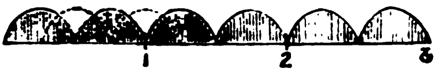


FIG. 32.—CURVE OF RECTIFIED OR COMMUTED ALTERNATING CURRENT.

But if by the addition of a simple split-tube commutator the alternate halves of these currents are reversed, so as to rectify their direction through the rest of the circuit, the resultant currents, though not continuous, will be of one sign only, as shown in Fig. 32, there being two currents generated during each revolution of the coil. The currents are now "rectified, or "redressed," as our continental neighbours say, but are not strictly continuous. To give *continuity* to the currents, we must advance from the simple 2-part commutator to a form having a larger number of segments, and

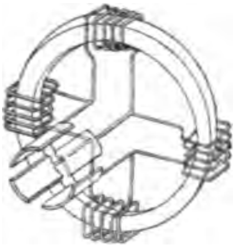


FIG. 33.—FOUR-PART RING ARMATURE (CLOSED COIL).

employ therewith a larger number of coils. The coils must also be so arranged that one set comes into action while the other is going out of action. Accordingly, if we fix upon our iron ring two sets of coils at right angles to each other's planes, as in Fig. 33, so that one comes into the position of best action while the other is in the position of least action (one being parallel to the magnetic lines when the other is normal to them), and their actions be superposed, the result will be, as shown in Fig. 34, to give a current which is continuous, but not steady, having four slight undulations per revolution. If any larger number of separate coils are used, and their effects, occurring at regular intervals, be superposed, a similar curve will be obtained, but with summits proportionately more numerous and less elevated. When the number of coils used is very great, and the overlappings of the curves are still more complete, the row of summits will form practically a straight line, or the whole current will be practically constant. As arranged in Fig. 33, the four coils are all united together in a *closed* circuit, the end of the first being united to the beginning of the second, and so forth all round, the last closing in to the first. In order to obtain greater uniformity of effect, the coils on the armature ought to be divided into a very large number of "sections" or "elements," which come in regular succession into the position of maximum effect at regular intervals one after the other. In Fig. 35 a sketch is given of a drum armature wound with two pairs of coils at right angles one to the other, and connected to a 4-part commutator. A little examination of Figs. 33 and 35 will show that each of the four "sections" is connected to the next in order to it; the whole of the windings constituting, therefore, a single *closed coil.* Also the end of

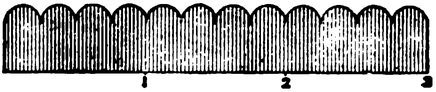


FIG. 34.—CURVE OF CONTINUOUS BUT NON-UNIFORM CURRENT.

one section and the beginning of the next are both connected with a segment of the commutator. In practice the commutator *segments* are not mere slices of metal tubing but are built up of a number of parallel bars of copper, hard-drawn, or drop-forged, such as may be seen in Fig. 38, p. 56. placed round the periphery of a cylinder of some insulating substance. It will also be noticed that, owing to the fact that there is a continuous circuit all round, there are at least *two paths* in which the current may flow through the armature from one brush to another, as in all the ring and drum armatures; of which, indeed, Figs. 33 and 35 may be taken as simplified instances. The same reasoning now applied to 4-part armatures holds good for those having a still larger number of parts, such as is shown in Fig. 36. Of these more will be said in the subsequent chapters. Let it suffice to say here that in closed-coil armatures, whether of the "ring" or the "drum" type, there are usually as many *segments* to the commutator as there are *sections* or groups of coils in the circuit of the armature. The special case of *open-coil armatures* is considered in Chapter XXII. In machines of this type the

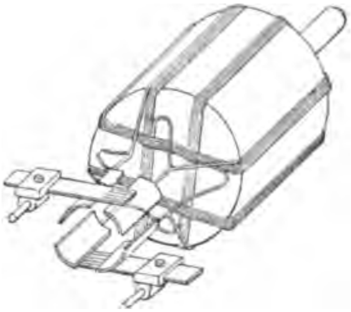


FIG. 35.—FOUR-PART DRUM ARMATURE (CLOSED COIL).

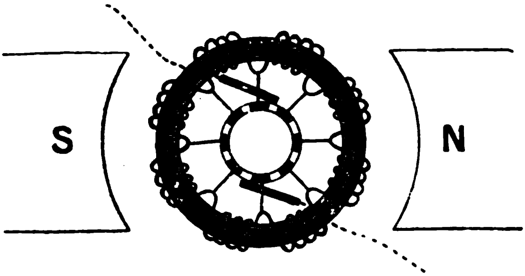


FIG. 36.—SIMPLE RING ARMATURE, SHOWING CONNEXIONS OF CLOSED COIL.

separate coils are not necessarily connected up together in series; and a special form of commutator is used instead of the usual arrangement of a large number of parallel bars.

So far, the only types of armature considered have been the "drum" type and the "ring" type; but these are not the only possible cases. The object of all such combinations of coils is to obtain the practical continuity and equability of current explained above. Theoretically, any figure of revolution around which the coils are symmetrically assembled would serve the purpose. Amongst such forms the sphere and the cone might be included, and have indeed been tried; but in practice the types of armature have resolved themselves into the following:—

(1) *Ring armatures,* in which the coils are grouped upon a ring whose principal axis of symmetry is its axis of rotation also.

(2) *Drum Armatures,* in which the coils are wound longitudinally over the surface of a drum or cylinder.

(3) *Pole armatures,* having coils wound on separate poles projecting radially all round the periphery of a disk or central hub.

(4) *Disk armatures,* in which the coils are flattened into a disk.

The ingenuity of inventors has been exercised in several directions:—The securing of practical continuity, the avoidance of eddy currents in the cores, the reduction of useless resistance, and the greatest specific utilization of material. Most inventors have been content to secure approximate continuity by making the number of sections numerous. Pacinotti's early dynamo had the coils wound between projecting teeth upon an iron ring. Gramme preferred that the coils should be wound round the entire surface of the annular iron core. To prevent wasteful eddy currents in the core, he constructed it of varnished iron wire. For ring cores flat core-disks of sheet iron are now universally preferred. For discoidal ring armatures the core is built of hoops. In ring armatures the parts of the copper coils which pass through the interior of the ring are inoperative in cutting magnetic lines, unless there are pole-pieces of the field-magnet projecting internally. Hence, in the ordinary forms of dynamo with exterior magnets the inner parts of the ring winding act merely as conductors and not as inductors, and offer a certain amount of wasteful resistance. But this resistance in well-designed machines is insignificant compared with that of the external circuit; and the disadvantage is small. In certain large German dynamos the ring is outside the field-magnets, so that the outer part of the windings are non-inductive or idle; and the currents are collected direct from the windings of the ring by brushes which trail on its periphery. The various modes of winding and connecting up the conductors on an armature are specially considered in Chapter XIII. A finished ring armature with its commutator and driving pulley is shown in Fig. 37.

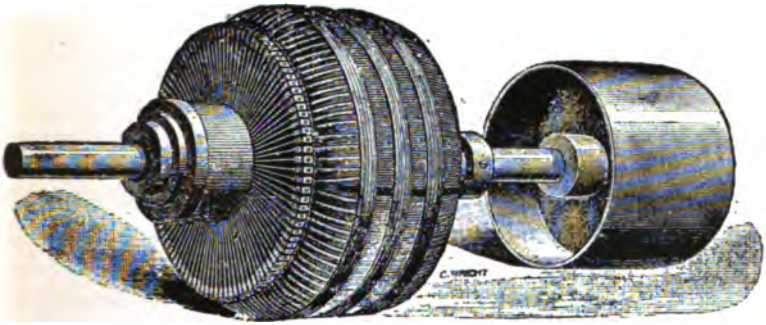


FIG. 37.—RING ARMATURE OF GRAMME DYNAMO.

Drum armatures, as first constructed by Siemens, had iron cores made of wire wound upon an internal non-magnetic nucleus. Weston substituted stamped core-disks of iron with teeth. A complete drum armature is depicted in Fig. 38, which shows the overlapping of the windings at the end of the drum, the connexions to the commutator, and the external binding wires that keep the coils from flying out. With the introduction of multipolar machines, the tendency in recent years has been to design armatures more and more in fly-wheel form with diameter much larger than the axial length.

Pole armatures, having the coils wound upon radially projecting poles, were devised by Allan, Lontin and Weston. The principle of Lontin's machines, in which the coils are connected to be re-entrant like the sections of a Gramme ring, is indicated in Fig. 39. This form has not proved successful for continuous-current machines, as the self-induction in each section of the winding is so great that the machines cannot run without sparking. Pole armatures are, however, used in some alternators, and in the Westinghouse arc-light machine.

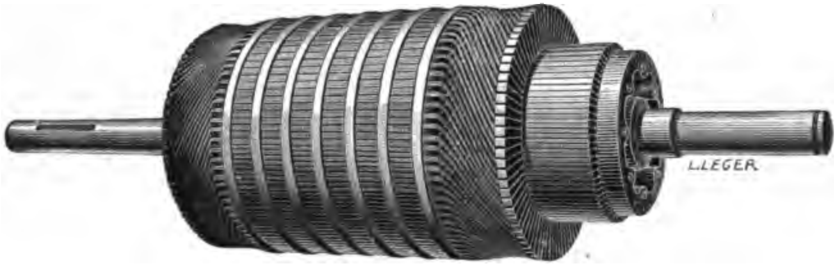


FIG. 38.—DRUM ARMATURE (ALLGEMEINE CO'S. PATTERN).

Disk armatures are differentiated into two kinds: (1) those in which the coils are grouped on a number of small bobbins, side by side, an arrangement suitable for alternate-current machines, such as those of Siemens, Ferranti and Mordey; (2) those in which the windings are made to overlap over a considerable angle of the periphery, as in the disk dynamos of Pacinotti, of Desroziers and of Fritsche, all of which are adapted to give continuous currents. A disk armature is

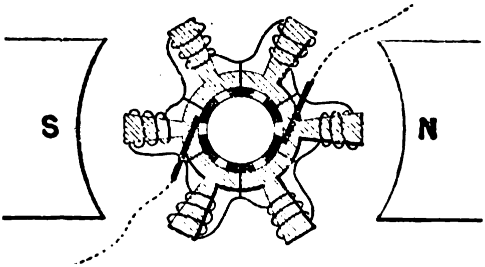


FIG. 39.—SIMPLE POLE ARMATURE SHOWING CONNEXIONS.

shown in Fig. 40, belonging to a Desroziers machine. But the mechanical difficulties attendant on this type have caused it to be abandoned for continuous-current machines. It is usual, in the disk form of armature, to dispense with any iron core; the armature being inserted in a narrow gap between the polar surfaces of the field-magnet.

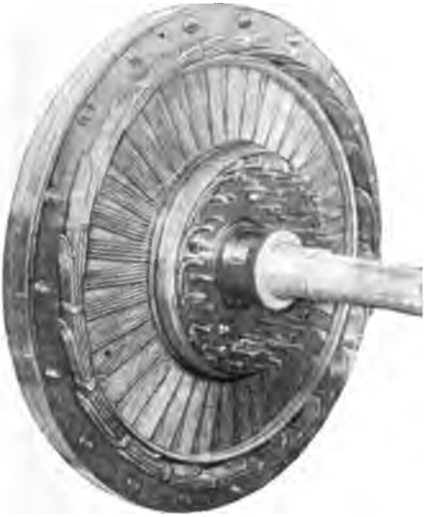


FIG. 40.—DISK ARMATURE OF DESROZIERS' MACHINE.

ARMATURE CORES.

Whenever iron is employed in armatures, it must be slit or laminated, so as to prevent the generation of parasitic eddy-currents. Such iron cores should be structurally divided in planes normal to the circuits round which electromotive-force is induced; or should be divided in planes parallel to the magnetic flux and to the direction of the motion. Thus, drum armature cores should be built of disks of thin sheet iron. Ring armatures, if of the cylindrical or elongated type, should have cores made up of rings stamped out of sheet iron and clamped together side by side; but if of the flat-ring type they should be built of concentric hoops. Cores built up of varnished iron wire, or of thin disks of sheet iron separated by varnish, asbestos, or paper, partially realize the required condition. The magnetic discontinuity of wire cores is, however, disadvantageous ; it is better that the iron should be without discontinuity in the direction in which it is to be magnetized. It should, therefore, be laminated into sheets, rather than subdivided into wires. Armature cores of solid iron are quite inadmissible, as currents are generated in them and heat them. Cores of solid metal other than iron—for example, of gun-metal or of phosphor-bronze—should on no account be used in any armature.

Segmental cores.—For all armature-cores exceeding 2 feet or so in diameter it is usual to stamp out the core disks in segments which are built up together into rings ; and, except in the case of some alternate-current machines, it is the practice to build up these segments so that they break joint, the segments of one layer overlapping the joints of the preceding layer, so as to secure general magnetic continuity. In multipolar armatures it is customary, though not necessary, to make the segments of the same angular breadth as a pair of poles. See, however, the examples in later Chapters.

FUNDAMENTAL POINTS IN DESIGN.

As has already been pointed out, the function of the field-magnet is to provide a large number of magnetic lines, whilst the function of the armature is to cut the magnetic lines so provided. The iron core of the armature may be regarded, therefore, as belonging to the magnetic circuit of the field magnet ; the true armature consisting of the rotating copper conductors. There is no electrical necessity for the iron core inside the armature to rotate ; indeed, in some ways it would act more efficiently if it did not. But purely mechanical considerations require that in rotating armatures of both ring and drum types the core should rotate with the coils. In all dynamos the electromotive-force is proportional at every instant to the rate at which the magnetic lines are being cut, and this will again be proportional to three quantities: (1) the magnetic flux or number of magnetic lines provided by the field-magnet; (2) the number of copper conductors connected together upon the armature; (3) the speed at which these conductors are driven. In alternate-current dynamos the rate of cutting is continually changing in a regular periodicity; in continuous-current machines the rate of cutting is automatically averaged and made steady by the method of grouping the conductors around the ring or drum in a re-entrant circuit, and connecting to the commutator. It is shown later, on p. 282, that, for continuous-current dynamos the electromotive-force generated in the revolving armature may be calculated as follows:—

Let the speed of the armature, or revolutions *per second*, be called n.

Let the number of conductors that are joined in series with one another around the armature be called Z.

Let the number of magnetic lines which pass into or out of the armature core from one pole be called **N**.

Let the number of volts of electromotive-force generated by the rotating armature be called E.

Then the following formula holds good for all ordinary parallel-wound armatures in which the number of paths through the armature is equal to the number of poles:—

$$E = n \times Z \times \mathbf{N} \div 100{,}000{,}000.$$

Example.—In a Kapp bipolar dynamo used at the Technical College, Finsbury, Z = 120; **N** = 7,170,000, at a speed of 780 revs. per min., or 13 revs. per sec., the whole electromotive-force generated is 111 volts.

In those armatures in which there is adopted a "series-grouping," or a "series-parallel-grouping" (see Chapter XIII.) the number of paths that are in parallel through the armature differs from the number of poles, and in these cases the formula becomes:—

$$E = n \times Z \times N \times \frac{p}{c} \div 100{,}000{,}000;$$

where p is the number of poles, and c the number of circuits that are in parallel.

For alternate-current machines the fundamental formula requires to be completed by the introduction of two additional factors. Such machines are usually multipolar, with but one single circuit or path through the armature; and the total effect must be increased by multiplying by the number P of pairs of magnetic poles that surround the armature. Or, since the frequency f of the current is equal to n P it may be substituted in the equation. Further, a constant k must be inserted, the numerical value of which (varying from 1·8 to 2·8 in actual machines) depends on the relative breadths of the coils and shape of the pole-pieces employed. The general formula for the volts generated in any alternate-current machine will then be:—

$$E = k \times P \times n \times Z \times N \div 100{,}000{,}000.$$

Example.—In a certain alternator built at Schenectady, $k = 2 \cdot 22$; $P = 12$; $n = 3 \cdot 33$, i.e. 200 revs. per min.; $Z = 960$; $N = 2{,}950{,}000$; $f = 40$; $E = 2 \cdot 22 \times 40 \times 960 \times 2{,}950{,}000 \div 10^8 = 2500$ volts.

From the above formulæ it will be seen that the electromotive-force at which any dynamo is to deliver its current is the product of three factors; and it can be increased by increasing any one of the three, or all of them. In a given machine Z is a constant, and N, the magnetic flux per pole, cannot be increased beyond the capacity of the iron core to carry magnetic lines. But if it is desired to design a new machine, obviously any value might be assigned to any of the three factors, provided the product came to the required amount. It is, therefore, a question of expediency whether in so designing a machine we will increase any one of the factors rather than any other. To increase N means using a larger cross section of iron, and a correspondingly big field-magnet, and therefore involves additional cost of iron. To increase Z means increasing the weight, and therefore the cost of the copper conductors; for the section of these depends on the current they have to carry, whilst the electromotive-force generated depends on their number, and on the rate at which they cut the magnetic lines. Moreover, experience shows that thus increasing the quantity of copper upon an armature core of given size involves, when once a certain limit is reached, the very serious difficulty that the current cannot be collected without sparking occurring at the brushes. To increase the speed *n* involves mechanical difficulties about lubrication and liability of the parts to fly out; in fact, mechanical considerations limit the speed. Moreover in the case of alternators the speed of any machine is fixed by the prescribed "frequency" of the alternating currents which it is to deliver. For many years modern practice has gone in the direction of keeping the speed slow, and in keeping down the relative amount of copper, the quantity of iron being relatively large; for not only so is the total cost of the machine less than it would be if the relative amounts of copper and iron were reversed, but the expense and trouble of maintenance is found to be less. Continuous-current machines with a relatively massive and powerful field-magnet are less prone to spark, require less attention to regulation, and need fewer renewals of the brushes and commutator than do those which have a comparatively weak field-magnet.

METHODS OF EXCITING THE FIELD MAGNETISM.

The five simple methods of exciting the magnetism that is to be utilised in the magnetic field may be grouped under two heads, according to whether the armature of the machine supplies the machine's own magnetism or whether the magnetism is provided for from some other source.

(i.) *Magneto-machine.*—In the oldest machines there was no attempt to make the machine excite its own magnetism, which was provided for it once for all by the employment of a permanent magnet of steel. Unfortunately, the permanent magnetism of steel magnets, even when after "ageing" it has settled down to a constant value, is less intense than the temporary magnetism which can be excited by a coil, necessitating permanent magnets of larger size than electromagnets.

The *magneto-electric machine* or *magneto-dynamo*, a diagrammatic drawing of which is given in Fig. 41, survives, indeed, in numerous small types of machines. It has the serious disadvantage of being both heavier and bulkier than other dynamos of equal capacity, because hard steel cannot be permanently magnetised to the same high degree as that to which wrought iron or mild steel or cast iron can be maintained by an exciting current.

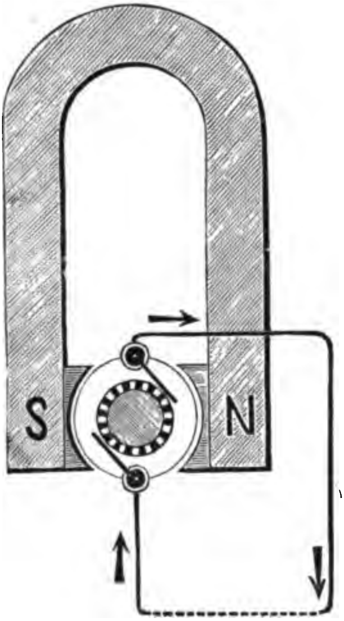


FIG. 41
THE MAGNETO-MACHINE.

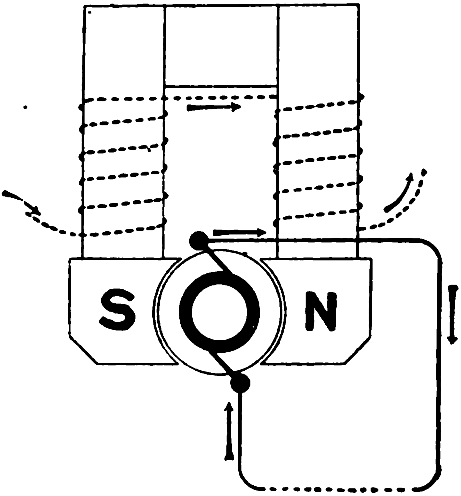


FIG. 42.
THE SEPARATELY-EXCITED DYNAMO.

(ii.) *Separately-excited Dynamo.*—It was an obvious step to substitute for steel magnets, electromagnets excited by means of currents from some independent source such as a voltaic battery. The *separately-excited dynamo* (Fig. 42) comes therefore second in the order of development. Though used by Faraday, this method did not come into acceptance until, in 1866, Wilde (see p. 14) employed a small auxiliary magneto-machine to furnish currents to excite the field-magnets of a larger dynamo. The separately-excited dynamo, in common with the magneto-machine, possesses the property that, saving for armature reactions, the magnetism in its field, and therefore the total electromotive-force of the machine, is independent of changes of resistance going on in the external circuit.

The dynamos of either of the preceding kinds can be governed in three different ways: by altering the speed, by putting the brushes forward beyond the neutral point, or by altering the magnetic flux through the armature. For long it has been the fashion to control the electromotive-force of small magneto machines by the device of providing a movable piece of iron, which could be placed more or less over the poles of the field-magnet, serving as a magnetic shunt to divert some of the magnetism from the armature. In the case of separately-excited machines there are two other methods of diminishing at will the effective magnetism, namely by weakening the exciting current, for example, by introducing less resistance into the exciting circuit, or by altering the number of turns of wire through which the existing current circulates around the field-magnet.

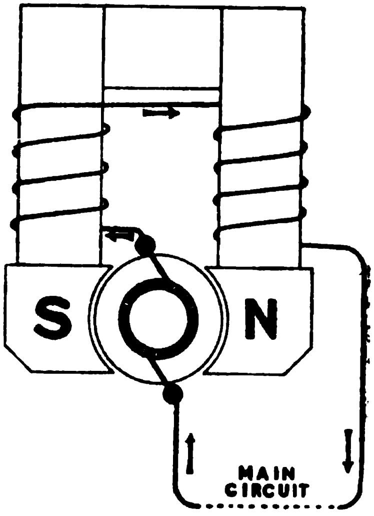


FIG. 43.—THE SERIES DYNAMO.

The elementary methods of making dynamos self-exciting are three in number: (1) the whole current from the armature may be carried through field-magnet coils that are connected in series with the main circuit; (2) a portion of the current from the armature may be diverted from the main circuit and carried through field-magnet coils of somewhat high resistance connected as a shunt; (3) the current required to excite the field-magnet may be procured either from a second armature revolving in the same field, or (if the armature consists of many coils) from some of the coils of the armature that may be separately joined up for that purpose.

(iii.) *Series Dynamo.*—The series-wound machine, or series dynamo (Fig. 43), possesses but one circuit. It has the disadvantage of not starting action until a certain speed has been attained, or unless the resistance of the circuit is below a certain limit ; the machine refusing to magnetize its own magnets when there is too much resistance and too little speed. The least speed of self-excitation is a measure of the goodness of its magnetic circuit. Series-wound machines are also liable to become reversed in polarity, a serious disadvantage, and one that unfits this type of machine for employment in electroplating or for charging accumulators. Any increase in the resistance of the series-wound dynamo lessens its power to supply current, because it diminishes the current in the coils of the field-magnet, and therefore diminishes the amount of the effective magnetism. When lamps are in series (as is common in an arc-light circuit) in the circuit of a series-wound dynamo, the switching on of an additional lamp both adds to the resistance of the circuit and diminishes the power of the machine to supply current. On the other hand, when lamps are in parallel across a pair of mains fed by a dynamo, if that dynamo is series-wound, the switching on of additional lamps not only diminishes the resistance of the circuit, but causes the field-magnets to be further excited by the increased current, so that the more lamps are put on, the greater becomes the risk of their getting too great a current.

(iv.) *Shunt Dynamo.*—In the shunt-wound machine (Fig. 44) the field-magnet is wound with many turns of fine wire, to receive only a small portion of the whole current generated in the armature. The coils are connected to the brushes of the machine, and constitute a by-pass circuit or shunt. Shunt machines are less liable to reverse their polarity than series machines. Owing to the somewhat greater cost of the fine wire of the shunt coil, they are slightly dearer in prime cost than series machines of equal power, but the expenditure of electric energy to keep up the magnetism is alike in both cases. It requires the same expenditure of electric energy to magnetize an electromagnet to the same degree, whether the coil consists of many turns of thin wire or of a few turns of thick wire, provided the weight of copper used in the coil be alike in the two cases. When a shunt machine is supplying lamps in parallel, the addition of lamps which brings down the net resistance of the circuit will increase the current, but not proportionally, for when the resistance of the main circuit is lowered, a little less current goes round the shunt and the magnetism drops a trifle; nevertheless, such a machine may regulate itself tolerably well if the internal resistance of its armature is very small. The electromotive-force of the shunt machine can be controlled by introducing a variable resistance into the shunt circuit.

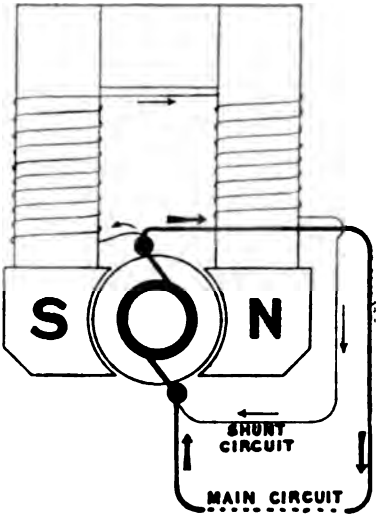


FIG. 44.—THE SHUNT DYNAMO.

A variety of the shunt method involves the use of a *third brush*, placed against the commutator at some point intermediate between the points of highest and lowest potential. The ends of the exciting coil are connected to the third brush and to one of the ordinary brushes so that the exciting coil receives a fraction of the volts generated in the armature.

(v.) *Separate-circuit Self-exciting Dynamo.*—There is yet a third species (Fig. 45) of self-exciting machine, in which the field-magnet coils are arranged to form part of a circuit entirely separate from the main circuit, but are supplied with currents from coils rotating in the field. There are two ways of carrying this into effect: (1) a second armature may be made to rotate between the same field-magnets in order to supply the exciting current, each armature having its own commutator; (2) a few of the armature coils may be connected up separately to a special commutator to supply an exciting current. The effect of the separate-coil method of excitation is almost identical with that of the shunt method, but it has the advantage that the current thus taken off for magnetizing may be taken at a low voltage; this being preferable in the case of machines for high voltages. For machines working at 1000 volts and over, the cost of the fine wire for winding a shunt would be excessive.

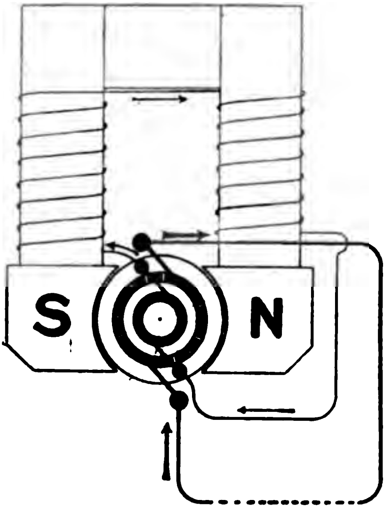


FIG. 45.—SEPARATE-CIRCUIT SELF-EXCITING DYNAMO.

Any of the five systems enumerated may be applied in continuous-current machines. Alternate-current machines must be separately-excited; though there are special methods of adapting some forms of alternator so as to be self-exciting and also to be self-compounding. Each of these five systems of exciting the field magnetism has its own merit for special cases, but none of them is perfect. Not one of these methods[1] will ensure that, with a uniform speed of driving, the electric pressure at the terminals shall be constant under all conditions of load.

If all the lamps in the circuit of a dynamo were required to be kept alight, all being turned on and turned off at once—in other words, if the output of the machine were constant—it would matter little how the magnetism of the field-magnet was excited, whether in main circuit or in shunt, provided the speed were kept constant. But for systems with a variable load, none of the simple methods of excitation enumerated above will insure regularity of pressure in the electric supply.

---

[1] An exception exists in the case of a shunt-wound machine if provided with Sayers' special device for enabling the brushes to be set with a backward lead. See p. 270.

Thanks, however, to the invention of combinations of windings, machines can be made which, when driven at a constant speed, give out their current at a constant pressure. These methods are carefully developed in Chapter XI. They are briefly described here also, so as to complete our summary of the methods of exciting the field-magnets.

Constant Pressure and Constant Current.—There are two distinct cases for which self-regulation is required.

As the function of a dynamo is to feed with sufficiency and regularity a system of lamps, and as those lamps are usually in practice[1] arranged either in parallel or in series, it is clear that in the former case there is required *a constant electric pressure* or *difference of potentials* between the mains, in other words an *invariable voltage*; while in the later case there is needed a *constant current*, or in other words an unvarying number of *amperes*. Distribution in series is exceedingly rare. It has been hitherto found impracticable to devise any mode of compound winding which will be self-regulating for maintaining an unvarying current. Other modes of regulation are resorted to in the case of machines for series arc lighting for which an unvarying current is needed. In almost all cases, whether for lighting or power, the aim is to make the generators maintain a constant voltage in the mains.

Suppose a dynamo to have an armature of zero internal resistance, without demagnetizing reactions, and to have its field-magnets excited from some independent constant source. At a constant speed it would give a constant potential at its terminals whatever the resistance in the circuit. But if it has internal resistance, the external pressure will be less than the whole electromotive-force, and the discrepancy will be greater according as the internal resistance and the current are greater; and if, as the load increases, there are armature reactions which tend to demagnetize the field-magnets, there will be a still further drop in the pressure in the mains. No separately-excited or shunt machine can therefore be self-regulating. The drop in the volts due to internal resistance and to armature reaction is nearly proportional to the current taken from the machine, being large when the current is large, and small when the current is small. Hence we may arrange to compensate these effects by an increase of the magnetism that shall also be proportional to the current. This is done by winding on a field-magnet a few turns of thick wire, or of copper strip, to carry the current on its way from the armature to the lamps. Such additional windings are called *compound winding*, or *compounding coils*; and a machine provided with this additional winding is called a *compound-wound dynamo* or a *compounded machine*. It will then give, within certain limits, a constant difference of potentials at its terminals. For distribution *at a constant pressure*, the following alternatives are therefore possible:—

---

[1] Occasionally incandescent lamps are arranged with two, three or more lamps in series, a number of such series being united in parallel across mains that are kept at a constant voltage. Less frequently a few lamps all in parallel with one another are inserted in the circuit of a series of arc lamps through which a current of constant strength is maintained. In any case, distribution must fall under one or other of the two cases considered.

I. *Non-automatic methods.*

(*a*) Separately excited dynamos, with hand regulators for raising the excitation as the load increases, and for lowering it as the load falls.

(*b*) Shunt dynamos, with similar hand regulation in their shunt circuits.

(*c*) Either of the above, with constant excitation, but with some means for artificially raising the speed by a few per cent. as the load increases.

II. *Automatic method.*

(*a*) Separately-excited dynamo, with a compound winding on its field-magnets.

(*b*) Shunt dynamo, with a compound winding on its field-magnets.

III. *Booster methods. See* Chapter XXIV.

METHODS OF COMPOUNDING TO GIVE CONSTANT VOLTAGE.

The following combinations are possible solutions of the problem of maintaining constant the voltage under a varying load.

(1) *Separate and Series* (Deprez).—A separate and constant excitation is provided from some independent source, so as to bring up the volts on open circuit to the required pressure. The additional excitation needed to raise the magnetism, so as to compensate for the drop in voltage that would otherwise occur, is provided by an additional series coil or compound winding, as indicated in Fig. 46.

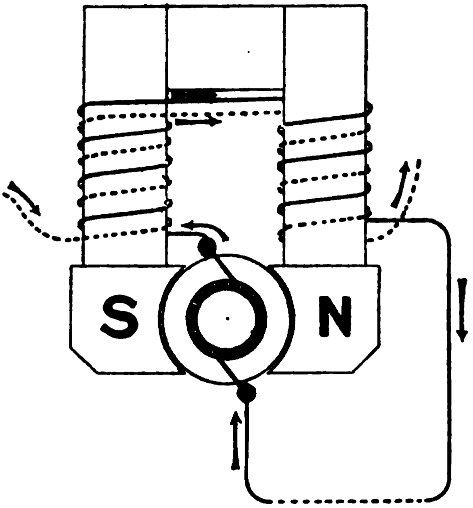


FIG. 46.—COMBINATION OF SEPARATE AND SERIES.

(2) *Separate-coil and Series.*—This method is not much used. For alternate-current dynamos a modification of it has been used with success, the "series" or main-circuit excitation being, in this case, replaced by an excitation derived from the main current by means of a small transformer, and rectified by a commutator.

(3) *Magneto* with auxiliary compounding machine.—The initial excitation may be that of a permanent magnet of steel: but Professor Perry suggested the more general solution of introducing into the circuit of a magneto-machine (driven at a uniform speed and such that it produces in the circuit, at no-load, the pressure which it is desired should be maintained) a small series-wound machine, which is also driven at a constant

speed, and which, as the load in the circuit is increased, will correspondingly generate an additional voltage proportional to the amperes, and therefore capable of compensating for the drop that would otherwise occur. This plan, which is applicable also if a separately-excited or shunt-wound dynamo is substituted for the magneto-machine, is the essential principle of the *booster*.

(4) *Shunt and Series.*—A dynamo having its coils wound as in Fig. 47, so that the field-magnets were excited partly by shunt current diverted from the main circuit, and partly by thick wire coils in series with the armature, was used by Brush as early as 1878. The voltage will depend upon the degree to which the magnetism is excited when the shunt is acting alone on open circuit. This is the arrangement commonly known as the *compound-wound* dynamo.

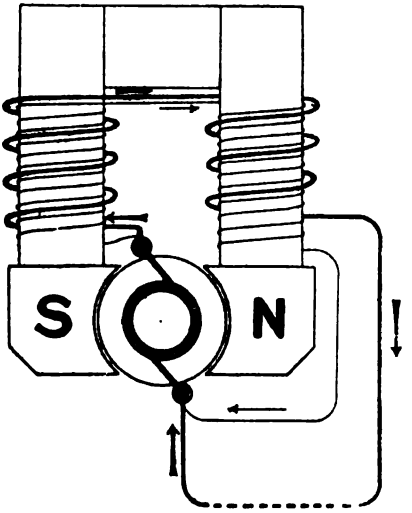


FIG. 47.—SHUNT AND SERIES.

By increasing the number of turns of wire in the compounding coils it is possible to over-compensate for the drop of voltage; with the effect that the voltage at the terminals of the machine will actually rise a little at full load. Such machines are described as *over-compounded.* Over-compounding is useful in certain cases to compensate for a drop in the voltage of the distributing system: for example, in the case of tramway generators in order to maintain constant the voltage at some distant point to which feeding mains run.

CHAPTER IV.

MAGNETIC PRINCIPLES; AND THE MAGNETIC PROPERTIES OF IRON.

As all dynamo-electric machines are based on magnetic principles, it is needful that these should be understood fully. If we once know the relation that subsists between the exciting current and the magnetism that is produced by it, we can apply this knowledge to the design of dynamos: for such knowledge will enable us to calculate beforehand the size of field-magnet and the number and gauge of windings that will be required in a dynamo that is to furnish any given amount of electric energy. It will be necessary first to define the terms used; then we shall give some account of the facts relating to the magnetic circuit, and of the properties of iron and steel of different kinds.

DEFINITIONS AND GENERAL PROPERTIES.[1]

Unit Magnetic Pole.—The unit magnetic pole is one of such a strength, that when placed at a distance of 1 centimetre (in air) from a pole of equal strength, it repels it with a force of 1 *dyne.*

Intensity of Magnetic Field.—We have seen in Chapter III. that every magnet is surrounded by a certain "field," within which magnetic force is observable. *The "intensity of the field" at any point is measured by the force with which it acts on a unit magnetic pole placed at that point.* Hence, *unit intensity of field is that intensity of field which acts on a unit pole with a force of one dyne.* There is therefore a field of unit intensity at a point one centimetre distant from the pole of a magnet of unit strength. Suppose a magnet pole, whose strength is m, placed in a field at a point where the intensity is $\mathcal{H}$, then the force will be m times as great as if the pole were of unit strength, and the amount of the force (in dynes) can be calculated by multiplying together the strength of the magnetism of the pole and the intensity of the field ; or,

---

[1] It is strongly recommended that the reader should make himself familiar with the elementary theory of magnetic phenomena. The author's *Elementary Lessons in Electricity and Magnetism*, published by Messrs. Macmillan and Co., will explain the terms and fundamental facts. The author's work on *The Electromagnet*, published by Messrs. E. & F. N. Spon, Ltd., contains a fuller account of the magnetic properties of iron, and the design and construction of electromagnets. Prof. Ewing's work on *Magnetic Induction in Iron and other Metals* is a standard book of reference. See also Du Bois' *The Magnetic Circuit.*

$$f = m \times \mathcal{H}.$$

The unit of intensity of a field is called one *gauss.*

Magnetic Lines.—It is possible, in every magnetic field, to draw through any point, a line in such a direction that it represents the direction of the magnetic force at that point of the field. The iron filing curves formed round magnets (Fig. 16, p. 39) show the forms of the otherwise invisible magnetic lines. Even when such lines are not actually drawn, they may be supposed to be drawn ; we may even conceive the whole of the space in the magnetic field to be traversed by such lines. Faraday was the first to give a quantitative signification to the conception of magnetic lines. We may use them to specify not only the *direction*, but also the *magnitude* of the magnetic forces by adopting the following convention :—*Let there be drawn as many lines per square centimetre of cross section of the field as there are dynes of force (on a unit pole) at the point in question.* The symbol $\mathcal{H}$ may then be read to mean *either* the number of dynes on a unit pole, or the number of lines per square centimetre in air ; it also may, as we shall presently see, be read to mean the amount of magnetomotive-force exerted, per centimetre of length, along the field.

The convention of magnetic lines enables us to see more clearly what is meant by *magnetic flux* ; for looking at Fig. 16 we see the lines issuing from one pole of the magnet like a stream spreading out over the surrounding space and flowing in at the opposite pole. Just as the total number of stream-lines of a liquid remains the same throughout the whole path, so the total number of lines of a magnet passing through a section of the path is the same whatever section we take, provided that our section cuts across the whole of the path. This total number is called the *magnetic flux,* and is symbolized[1] by the letter N.

If the area of section of this core is denoted by the letter A, the density of the magnetic flux will be equal to N ÷ A. When the sectional area is given in square inches the letter used to denote the *flux-density* (i.e. the number of magnetic lines per square inch), is B. In cases where the area is given in square centimetres, the letter used for the flux-density will be $\mathfrak{B}$. The magnetizing forces required to excite any required flux-density in the magnetic circuit of a dynamo are obtained by causing an electric current to circulate around the iron core. It is found that the magnetizing force thus produced is proportional both to the amount of current (i.e. the number of *amperes*) so flowing, and to the number of times it circulates around the core (i.e. the number of *turns* in the magnetizing coil). In other words, the magnetizing force is proportional to the number of *ampere-turns.* For brevity we sometimes describe the total number of ampere-turns of circulation of current around a core as "the *excitation.*" It goes without saying that the higher the flux-density required, and the greater the length of the iron through which the magnetic flux is to be driven, the greater is the amount of excitation needed. To drive a magnetic flux through air requires a much greater amount of excitation than is required for an equal flux-density through an equal length of iron. The coefficients used in calculating air-gaps are mentioned on p. 92. For example, suppose it was stated that the magnetizing forces were such in some case that $\mathcal{H} = 50$, this would mean that they were so strong that if applied to a layer of air

---

[1] Many continental writers adopt the symbol Φ for the magnetic flux, in defiance of the recommendations of the Frankfurt Congress of 1891 that Greek letters should be used only for angles, and for coefficients such as specific resistance, permeability, &c.

1 centimetre thick they would produce in the air a flux-density of 50 lines per square centimetre. If applied to an equal length of iron, the resulting flux-density $\mathfrak{B}$ would be immensely greater, since iron is much more permeable magnetically. The ratio of $\mathfrak{B}$ to $\mathfrak{H}$ in any material is called its *permeability.*

Magnetic Units.—The *line* is thus the unit of magnetic flux, and as it is a very small unit it will be convenient to use with it the prefixes *kilo* and *mega* ; one *kiloline* being 1000 lines, and one *megaline* being 1,000,000 lines. The Paris Congress of 1900 adopted the name *gauss* as that of the unit of intensity of field, one *gauss* signifying one line per square centimetre. The same Congress also named one *line* as one *maxwell*, but everybody still uses the term *line.*

British engineers generally prefer to describe the intensities of magnetic fields in *lines per square inch,* instead of in *gausses.* An intensity of one *gauss* equals 6·45 lines per square inch.

The American Institute of Electrical Engineers has proposed the name *gilbert* for the C.G.S. unit of magnetomotive-force ; being equal to $10 \div 4\pi$ of an ampere-turn. To convert ampere-turns into gilberts, one must multiply by $4\pi \div 10$, or by 1·257.

Magnetic Circuit.—The lines pass through the bar-magnet, Fig. 16, as well as the surrounding space, and thus make a complete *magnetic circuit.* If the ends of the bar were bent round and joined, so as to form a completely continuous ring, then all the lines would circulate within the metal of the magnet, and none in the air surrounding it. We should then speak of the ring as a *closed magnetic circuit.* In the dynamo we try to attain this metallic continuity of the circuit as nearly as possible, consistently with the movability of the rotating parts.

Though the definition of a magnetic line in the air is connected with the force upon a magnetic pole, we are not so much concerned (while considering dynamos), with the forces (exerted on poles by the lines), as with that other phenomenon, the induction of an electromotive-force when a conductor is moved across the lines. Indeed, though we have said that the magnetic lines are continuous throughout the entire circuit, it is really only in so far as their property of generating an electromotive-force is concerned, that they can be regarded as continuous; for the force inside a magnetic material, such as iron, is not represented by the number of magnet lines per square centimetre, as will be shown when we come to speak of magnetomotive-force. It is only in air, and equally non-magnetic substances that the force is represented by the number of lines per square centimetre. We therefore rather use the expression "magnetic lines," when speaking of the flux through magnetic material, in contrast to "the lines of force" which emerge into the air. The two are continuous throughout the circuit, and in the air the magnetic lines are the lines of force Where the lines which represent the direction and amount of any vector quantity, as, for example, magnetic lines or lines of electric flow, are closed on themselves so as to form a circuit, the distribution of the vector quantity is said to be *circuital.* The number of magnetic lines per centimetre of cross section of the magnetic material is aptly called the *flux-density*, and is usually denoted by $\mathfrak{B}$. The magnetic force in the material is as before denoted by $\mathfrak{H}$ which in fact represents the number of magnetic lines that would exist in the space if the magnetic material were replaced by air while the same causes producing magnetization still existed.

The idea of a magnetic circuit was more or less familiar to electricians fifty years ago. Faraday[1] considered that he had *proved* that each magnetic line constitutes a closed curve; that the path of these closed curves depended on the magnetic conductivity of the masses disposed in proximity; that the magnetic lines were strictly analogous to the lines of electric flow in an electric circuit. He spoke of a magnet surrounded by air being like unto a voltaic battery immersed in water. He even saw the existence of a power, analogous to that of electromotive-force in electric circuits, though the name

---

[1] *Experimental Researches*, vol. iii. arts. 3117, 3228, 3230, 3260, 3271, 3276, 3294 and 3361.

magnetomotive-force is of more recent origin. The same idea is more or less implicitly recognised in the latter half of the magnetic papers in Lord Kelvin's collected volume on Electrostatics and Magnetism. Rowland[1] in 1873 expressly adopted the reasoning and language of Faraday's method in the working out of some new results on magnetic permeability, and pointed out that the flow of magnetic lines of force through a bar could be subjected to exact calculation; the elementary law, he says, "is similar to the law of Ohm." Writing R for the "resistance to lines of force," M for "magnetizing force of helix," and Q for number of "lines of force in a bar at any point," he wrote, for a particular case (a ring-magnet, having therefore a closed magnetic circuit), the equation,

$$Q = \frac{M}{R};$$

an equation for magnetic circuits which every electrician will recognise as being precisely like Ohm's law. He applied the calculations to determine the permeability of certain specimens of iron, steel and nickel. In 1882,[2] and again in 1883,[3] R. H. M. Bosanquet brought out at greater length a similar argument, employing the extremely apt term *magnetomotive-force*, to connote the force tending to drive the total flux of magnetic lines through the *magnetic resistance* (or *reluctance*, as Heaviside has termed it), of the circuit. In these papers the calculations were reduced to a system, and deal not only with the specific properties of iron, but with problems arising out of the shape of the iron. Bosanquet showed how to calculate the several reluctances of the separate parts of the circuit, and then add them together to obtain the total reluctance of the magnetic circuit. In 1884 Rowland gave similar formulæ for the field-magnets of dynamos.

---

[1] *Phil. Mag.*, series iv. vol. xlvi. August 1873. "On Magnetic Permeability and the Maximum of Magnetism of Iron, Steel, and Nickel."

[2] *Proc. Roy. Soc.*, xxxiv. 445, December 1882.

[3] *Phil. Mag.*, series v. vol. xv. 205, March 1883. "On Magneto-motive Force." Also *ibid.*, vol. xix. February 1885; and *Proc. Roy. Soc.*, No. 223, 1883. See also *Electrician*, xiv. 291, February 14, 1885.

In 1886, Mr. Gisbert Kapp,[1] and independently Drs. J. and E. Hopkinson,[2] introduced magnetic-circuit calculations into the designing of dynamo-electric machines. These we shall further consider on p. 108.

We have seen that N, the magnetic flux flowing out of or into one pole of the field-magnet, is an important quantity in the determination of the electromotive-force of a dynamo. As the amount of this flux depends on (i.) the magneto-motive force, and (ii.) the reluctance of the magnetic circuit, it is necessary to give some consideration to these two quantities.

1. *Magnetomotive-Force* or Total Magnetizing Power of Electric Current circulation in a Coil.—It is found that when a current flows along in a wire that is coiled in several turns around a core (Fig. 48). and is thus made to circulate around an interlinked magnetic circuit, the magnetizing power is proportional both to the strength of the current so circulating and to the number of turns in the coil. The magnetizing power is independent of the size or material of the wire, and of its shape, and is the same whether the spirals are close together or wide apart. If S stand for the number of *spirals* in the coil, and C be the number of *amperes* of current that are flowing, then C multiplied by S will be the number of *ampere-turns* of circulation of current. It is experimentally proved that twenty amperes circulating around five turns exert precisely the same magnetizing power as one ampere circulating one hundred times, or as one hundred amperes circulating once around the core. In each of these cases the

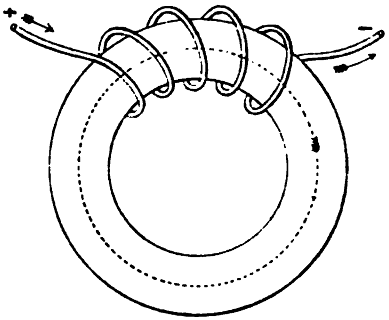


FIG. 48.—MAGNETIZING COIL WOUND AROUND A MAGNETIC CIRCUIT.

---

[1] *Journal Soc. Telegraphic Engineers and Electricians*, xv. 524–529, November 11, 1886. "On the Predetermination of the Characteristics of Dynamos."

[2] *Phil. Trans.*, part i. p. 331, 1886.

circulation of current is one hundred ampere-turns. To calculate from this the value, in absolute C.G.S. units, of the magnetomotive-force, it is requisite to multiply the ampere-turns by $\frac{4}{10}\pi$, or by $1{\cdot}257$. Or, in symbols,

$$\text{Magnetomotive-force} = 1{\cdot}257 \times \mathrm{C\,S}.$$

It is possible to avoid the use of this multiplier by taking the ampere-turns themselves as the magnetomotive-force. Indeed, this is the way adopted in practical calculations; see Chapter VI., below.

Some writers[1] call the magnetomotive-force the "line-integral of the magnetic forces." The reason is as follows:—In a field of intensity $\mathcal{H}$, a unit magnetic pole experiences a force numerically equal to $\mathcal{H}$; and if the unit were moved against this force once around a closed path of length l (like the dotted line in Fig. 48), the work done would measure the integral magnetic force. Hence along a length l in a field of intensity $\mathcal{H}$ the magnetomotive-force is equal to $\mathcal{H} \times l$. Hence it also follows that the intensity of the field along a uniformly wound coil is expressed by the formula:—

$$\mathcal{H} = 1{\cdot}257 \times \mathrm{C\,S} \div l.$$

In other words $\mathcal{H}$ is proportional to the *ampere-turns per unit of length.*

This formula would enable one to calculate the intensity of the field $\mathcal{H}$ down the middle of a long solenoid, the bobbin of which being l centimetres long, carried S turns of wire in which the current was C amperes.

Transposing, we find that the number of *ampere-turns per centimetre of length* will have the value

$$\frac{\mathrm{C\,S}}{l} = \frac{10}{4\pi}\mathcal{H}.$$

And, as 1 inch = 2·54 centimetres, we shall have for the number of *ampere-turns per inch* length of material, the value

$$\frac{\mathrm{C\,S}}{l''} = \frac{2{\cdot}54 \times 10}{4\pi}\mathcal{H} = 2{\cdot}02\,\mathcal{H}.$$

---

[1] See Maxwell's *Electricity and Magnetism*, vol. ii. art. 499; or S. P. Thompson's *Elementary Lessons on Electricity and Magnetism* (edition of 1900), p. 334.

Hence, if we have already got, for any specimen of iron, the curve connecting $\mathcal{B}$ and $\mathcal{H}$, we can at once change the $\mathcal{H}$ values for the more convenient *ampere-turns per inch* by changing the scale of the abscissæ; the point, for example, marked 50 on the $\mathcal{H}$ axis will now read 101 on the scale of ampere-turns per inch.

In fact $\mathcal{H}$ multiplied by 0·7958 gives the number of ampere-turns per centimetre of magnetic path. Or $\mathcal{H}$ multiplied by 2·02 gives the number of *ampere-turns per inch.*

Examples.—(i.) A solenoid which is 24 inches long is wound with 400 turns of wire and is traversed by 16·5 amperes. What will be the intensity of the field at the middle of the tube? The ampere-turns are $16{\cdot}5 \times 400 = 6600$; the ampere-turns per inch are 275; and dividing by 2·02 gives $\mathcal{H} = 136{\cdot}1$ gausses.

(ii.) In the above solenoid, what current will produce a field of intensity $\mathcal{H} = 100$ gausses? This will require $100 \times 2{\cdot}02 = 202$ ampere-turns per inch; or $202 \times 24 = 4848$ ampere-turns in total. Dividing 4848 by 400 gives the required current as 12·12 amperes.

It is clear that we may read such an expression as $\mathcal{H} = 50$ in several ways. It may be read (1) that the intensity of the field is 50 gausses; or (2) that the field will be such that it would exert a force of 50 dynes on unit pole; or (3) that its intensity would be represented by 50 lines per square centimetre in air; or (4) that there is a magnetomotive-force of 50 gilberts per centimetre; or (5) that there will be required, approximately, 50 ampere-turns for each half-inch of length.

There are some analogies between a magnetic circuit and an electric circuit, which considerably simplify the magnetic principles relating to dynamo construction.[1]

Just as there are some materials which conduct the electric current better than others, so there are some materials which conduct the magnetic flux better than others. The reluctance or resistance of a circuit in each case is proportional to the length of the path, to the reluctivity or resistivity of the material, and inversely proportional to the cross section of the path. Just as in a battery the total electromotive-force is made up of the separate electromotive-forces of all the cells joined in series, so the total magnetomotive-force in a magnetic circuit is the sum of the magnetomotive-forces separately produced by each coil of wire. If the magnetic circuit is branched (as in the Manchester dynamo shown in Fig. 60, No. 24), then the coils on the separate branches do not have their forces added together, but are analogous to batteries placed in parallel with each other.

---

[1] It should be observed that, though for the purpose of this simplification, it is allowable to draw an analogy between an electric circuit and a magnetic circuit, the true magnetic analogue of an electric circuit (in which energy is being continually transported) would be a circuit in which energy is being transported by the passage of "free magnetism;" but no conductors of magnetism in this sense are as yet known.

We have a difference of magnetic potential between the ends of core wound with a magnetizing coil just as we have a difference of electric potential at the terminals of a cell. As we go along the magnetic circuit the potential falls by an amount equal to the reluctance of the path multiplied by the total flux. The iron inside a magnetizing coil may be said to be for the purpose of diminishing its "internal" reluctance. We have stout iron frames for our dynamos in order that the magnetic pressure of the coils may be transferred to the armature without appreciable "drop." The fall of magnetic potential in a column of air per centimetre of length is numerically equal to the flux-density. Therefore, to calculate the magnetomotive-force necessary to create a certain flux-density in a certain air-space, we have only to multiply the flux-density by the length of the air-space.

Thus to produce a flux-density of 10,000 lines per square centimetre in an air-gap 1 centimetre in length will require a magnetic pressure of 10,000 units, the unit being the magnetomotive force required to produce unit flux-density in an air-space 1 centimetre in length. One ampere-turn produces a magnetomotive-force of $4\pi \div 10$ gausses, so that to produce a flux-density of 10,000 in an air-gap 1 centimetre in length will require $\frac{10{,}000}{1 \cdot 257}$ ampere-turns. We might calculate the ampere-turns required on a dynamo field-magnet by multiplying the flux-density by the total length (in centimetres) of air-gap and dividing by 1·257, and then add some further turns to make up for the drop in magnetic potential in the iron circuit; but it is more usual to find the total reluctance of the circuit and multiply by the total flux in the manner shown in Chapters VI. and XIX.

2. *Reluctance of Magnetic Circuit.*—We have seen that, other things being equal, the total flux in a circuit is inversely proportional to the reluctivity of the materials of which it is composed; it is directly proportional to the *permeability* which is the reciprocal of *reluctivity.*

The *permeability* of a material is the numerical coefficient which expresses the ratio between flux-density $\mathcal{B}$, and the magnetizing force[1] $\mathcal{H}$. For instance, if a column of air is subjected to a magnetizing force $\mathcal{H}$, the number of magnetic lines per square centimetre of cross section, in other words, the flux-density $\mathcal{B}$ is equal to $\mathcal{H}$; therefore the ratio $\frac{\mathcal{B}}{\mathcal{H}} = 1$ and we say the permeability of the air is 1. If we take a piece of iron and subject it to the same magnetizing force $\mathcal{H}$ we find that $\mathcal{B}$ is very much greater. For example, a certain specimen of iron, when subjected to a magnetic force capable of creating, in air, 50 magnetic lines to the square centimetre, was found to be permeated by no fewer than 16,062 magnetic lines per square centimetre. Dividing the latter figure by the former gives 321 as the value of the permeability, that is to say, the permeability of the iron at this stage of the magnetization is 321 times that of air. The permeability, or ratio of $\mathcal{B}$ to $\mathcal{H}$, is usually denoted by the Greek letter μ. The permeability of such non-magnetic materials as silk, cotton and other insulators, also of brass, copper and all the non-magnetic metals, is taken as unity, being practically the same as that of the air.

---

[1] The following are the various ways of expressing the three definitions:—

$\mathcal{B}$—The number of lines per square centimetre in the material.
The flux-density.
The magnetic displacement.
The internal magnetization.
The magnetic induction.
The induction.
The intensity of the induction.
The permeation.

$\mathcal{H}$—The number of lines per square centimetre that there would be in air.
The magnetizing force at a point.
The magnetic force at a point.
The intensity of the magnetic force.
The rate per cm. of fall of magnetic potential.
The magnetomotive-force per centimetre length.

μ—The magnetic permeability.
The permeability.
The specific conductivity for magnetic lines.
The magnetic multiplying power of the material.

The permeability of iron, however, varies very greatly with the degree to which it has been magnetized. In all kinds of iron (after passing the initial stage mentioned below) the magnetizability of the material becomes diminished as the actual magnetization is pushed further; there is in fact a tendency to magnetic *saturation.* In other words, when a piece of iron has been magnetized up to a certain degree, it becomes, from that degree onwards, less permeable to further magnetization, and though actual saturation is never reached, there is a practical limit beyond which the magnetization cannot well be pushed. The permeability diminishes as the magnetization is pushed to higher stages. The practical limit of the flux-density, $\mathcal{B}$, in good wrought iron and in mild steel, is about 20,000 magnetic lines to the square centimetre; and in cast iron the practical saturation limit is nearly 12,000 lines per square centimetre. In square inch units these limits are: in wrought iron and mild steel B is about 125,000 or 130,000 lines per square inch, and in cast iron the maximum B is about 70,000 lines per square inch.

The *reluctance* or *magnetic resistance* of a long bar or cylinder of iron is obviously proportional to its length, and inversely proportional to its cross-section. It is also inversely proportional to its permeability.

In designing electromagnets, before calculations can be made as to the size of a piece of iron required for the core of a magnet for any particular purpose, it is necessary to know the magnetic properties of that piece of iron; for it is obvious that if the iron be of inferior magnetic permeability, a larger piece of it will be required in order to produce the same magnetic effect as might be produced with a smaller piece of higher permeability. Or again, the piece having inferior permeability will require to have more copper wire wound on it.

CURVES OF MAGNETIZATION.

A convenient mode of studying the magnetic facts respecting any particular brand of iron is to plot on a diagram the curve of magnetization—*i.e.* the curve in which the values, plotted horizontally, represent the magnetic force $\mathcal{H}$, and the values plotted vertically those that correspond to the respective flux-density, $\mathcal{B}$.

Thirty-five samples of various irons of known chemical composition were examined by Hopkinson,[1] the two most important for present purposes being an annealed wrought iron and a grey cast iron, as used by Messrs. Mather and Platt in the construction of dynamo machines.

The upper curve, Fig. 49, gives the behaviour of *annealed wrought iron.* The ascending line shows the relation between the intensity of the magnetizing force $\mathcal{H}$ and the flux-density $\mathcal{B}$ during the process of increasing the magnetizing force from zero to about 220; and the descending line shows the same relation during the process of decreasing the magnetizing force to zero, and then reversing it so as to remove the residual magnetic lines. The lower curve shows the behaviour of *grey cast iron.*

Every sample of iron will show, on being tested, a similar set of facts which can be plotted down as a curve that is characteristic of the relation in question; but the curves for cast iron and hard steel always lie lower than those for wrought iron. Moreover, it will usually be noticed that when a fresh piece of iron or steel is subjected to a gradually increasing magnetising force, the lowest part of the curve presents near its origin a small concavity (see Fig. 49) showing that there is a certain stage where under small magnetizing forces the permeability is greater than at the initial stage.

---

[1] *Phil. Trans.*, pt. ii. p. 455, 1885.

This concavity is more pronounced in the case of hard iron and of steel than in the case of soft iron. But the curves differ in detail even in different specimens of the same sort of iron.

In Fig. 50 are given seven curves,[1] relating to soft iron, hardened iron, "mild steel," [2] annealed steel, hard-drawn steel, cast iron and glass-hard steel.

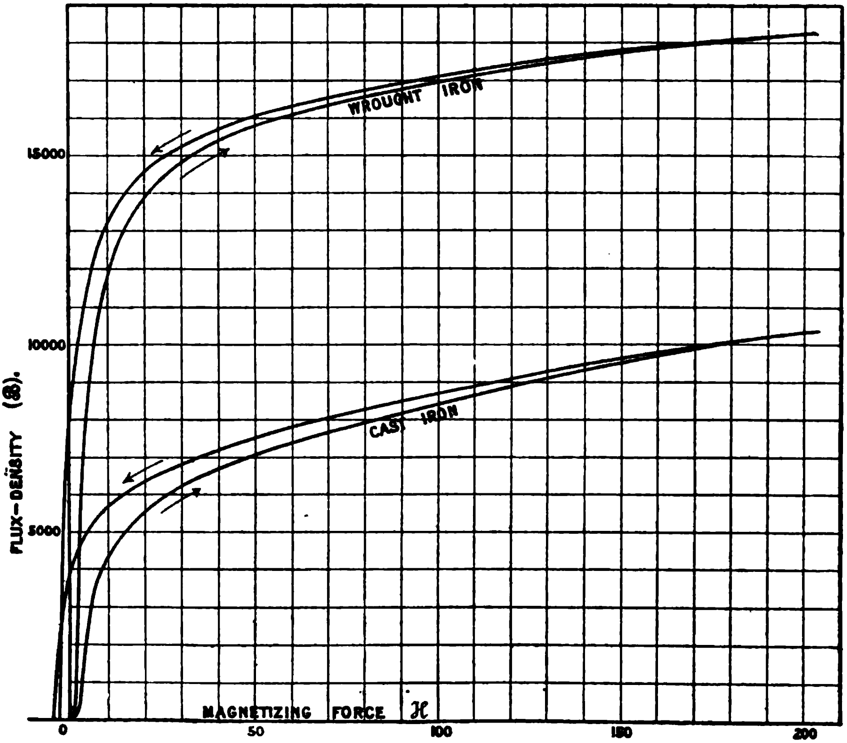


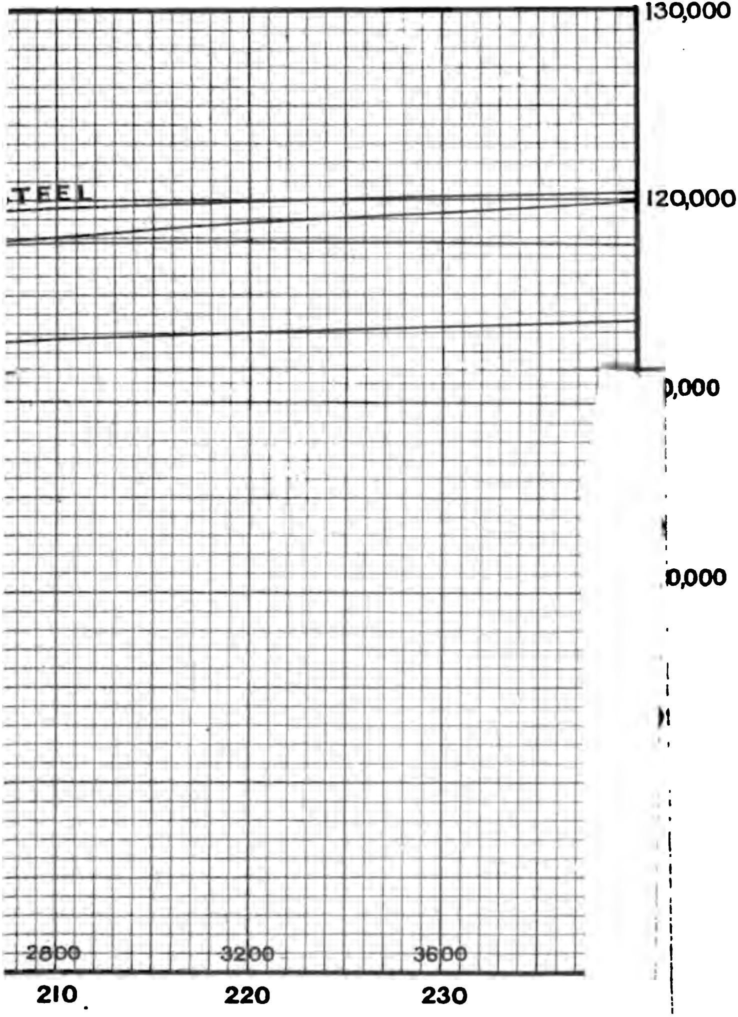
FIG. 49.—HOPKINSON'S CURVES OF MAGNETIZATION OF IRON.

In designing dynamos it is convenient to have for reference a series of curves such as Fig. 50, made by observation on samples of the same iron as it is intended to use in construction. Plate I. gives such curves in engineers' units. The

---

[1] *Phil. Trans.*, 1885. [2] See p. 89 as to the nature of so-called "mild steel."

Plate 1.



te can be had separate from the Publishers,
on transparent paper.— Price 7.^{d} post free.

particular brands of iron to which these curves refer are :—The fine soft sheet iron sold by Messrs. Sankey, called "Lohys" iron ; the cast steel for dynamo field-magnets manufactured by Messrs. Edgar Allen of Sheffield ; the very mild magnet-steel of Messrs. Hadfield of Sheffield ; Krupp's dynamo magnet-steel ; an ordinary cast-iron having about 0·2 per cent. of "combined" carbon, tested by Mr. Parshall ; an American steel of extraordinarily high permeability, produced by the acid open-hearth process, tested by Mr. H. S. Meyer ; and a soft ordinary Styrian sheet iron, tested by Herr Blathy.

In the drawing-office each dynamo-designer ought to

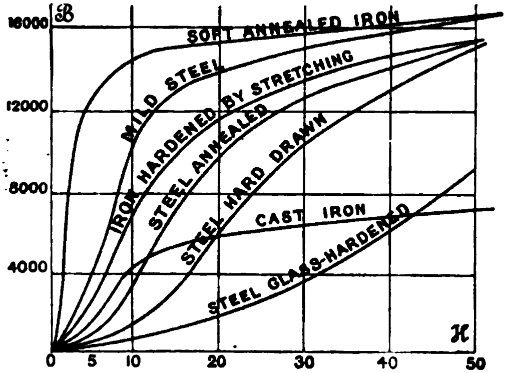


FIG. 50.—CURVES OF MAGNETIZATION OF VARIOUS SORTS OF IRON.

provide himself with similar curves for the particular brands of iron and steel which he uses. All the good makers of iron and steel for dynamo purposes will furnish curves for the materials which they produce. The additional curves given in Fig. 51 relate to wrought iron when worked at very high flux-densities ; one is due to Mr. Parshall, the other relates to Messrs. Sankey's special quality of armature stampings. Such curves find their principal application in calculating the ampere-turns required for the teeth of slotted armatures, which are frequently worked at very high flux-densities ; but they must be used with caution, on account of the limited amount of knowledge at present available on this subject. The curves in the lower right-hand corner of Plate I. relate also to

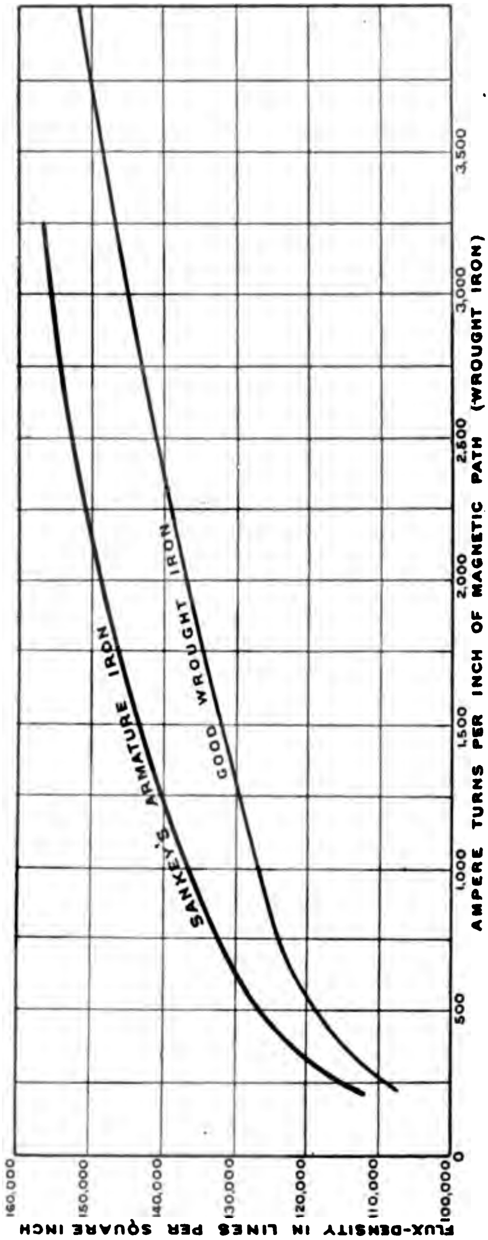


Fig. 51.—Magnetization-Curve at Very High Densities.

magnetization in very strong fields, the upper one being the iron examined[1] by Mr. H. S. Meyer.

Barrett[2] has recently found that a particular steel containing $2\frac{1}{4}$ per cent. of aluminium, made by Hadfield, of Sheffield, has a higher permeability than any known brand of wrought iron.

Looking at the curves of Plate I., one sees that if one wishes to know, for example, how much magnetizing force is required to produce a flux-density of, say, $B = 100{,}000$ lines per square inch, in Hadfield's magnet-steel, one follows out the curve up to the level of 100,000, and then dropping perpendicularly on to the horizontal scale one observes that it will require 35 ampere-turns per inch length of the iron.

Example.—Find the number of ampere-turns of excitation necessary to drive a flux of 12,000,000 lines through a cast-iron yoke, the cross-section of which is 300 square inches, and the length 17 inches. Since 300 square inches carry 12,000,000 lines, the flux-density B will be 40,000 lines per square inch. Reference to the curve for cast iron in Plate I. will show that this will require 75 ampere-turns per inch; and as the iron is 17 inches long the answer is $17 \times 75 = 1275$ *ampere-turns.*

The values for $\mathfrak{B}$, μ and $\mathfrak{H}$ for Hopkinson's carefully annealed specimen of soft iron are given in square centimetre units in Table I. (p. 88), and in square inch units in Table II.

With wrought iron the permeability, for small flux-densities, is not very great, but increases as the density is increased up to about 5000, at which stage $\mu = 3000$. An increase beyond this point decreases the permeability until when $\mathfrak{B} = 16{,}000$ the permeability has fallen to 400, and at $\mathfrak{B} = 20{,}000$ it is about 100. Thus it is not economical to push $\mathfrak{B}$ much beyond 16,000. Table III. gives similar values for mild cast steel. In dynamo field-magnets of steel, $\mathfrak{B}$ is generally somewhere about 16,000, so that the permeability of the material at this point is the criterion of the value of different materials for field-magnets. Now, looking at the curve for *mild cast*

---

[1] *Elektrot. Zeitschrift*, xxxv. 769, September 12, 1901.

[2] See *Journ. Inst. Elec. Engineers*, xxxi. 709, 1902.

TABLE I. (SQUARE CENTIMETRE UNITS).

Annealed Wrought Iron.			Grey Cast Iron.		
$\mathcal{B}$	μ	$\mathcal{H}$	$\mathcal{B}$	μ	$\mathcal{H}$
5,000	3000	1·66	4,000	800	5
9,000	2250	4	5,000	500	10
10,000	2000	5	6,000	279	21·5
11,000	1692	6·5	7,000	133	42
12,000	1412	8·5	8,000	100	80
13,000	1083	12	9,000	71	127
14,000	823	17	10,000	53	188
15,000	526	28·5	10,000	37	292
16,000	320	50			
17,000	161	105			
18,000	90	200			
19,000	54	350			
20,000	30	666			

TABLE II. (SQUARE INCH UNITS).

Annealed Wrought Iron.			Grey Cast Iron.		
$B_{\prime\prime}$	μ	$H_{\prime\prime}$	$B_{\prime\prime}$	μ	$H_{\prime\prime}$
30,000	2926	10·2	25,000	833	30
40,000	2857	14	30,000	445	53·5
50,000	2392	20·9	40,000	245	163
60,000	2166	27·7	50,000	112	447
70,000	1750	40	60,000	64	940
80,000	1368	63	70,000	40	1750
90,000	856	105			
100,000	407	245			
110,000	161	686			
120,000	64	1850			
130,000	28	4500			
140,000	18	7630			

TABLE III. (MESSRS. EDGAR ALLEN AND CO'S. DYNAMO CAST STEEL).

Square Centimetre Units.			Inch Units.	
$\mathfrak{B}$	μ	$\mathcal{H}$	B	Ampere-turns per inch.
2000	952	2·1	12,500	4·5
4000	1428	2·8	25,000	5·6
8000	1634	4·8	50,000	9·6
12,000	1250	9·6	60,000	12
14,000	940	14·9	80,000	21
16,000	585	27·4	90,000	30
17,000	377	45	100,000	47
18,000	231	78	110,000	93
19,000	148	130	120,000	223

steel, it will be seen that, though the permeability for flux-densities of the order of 10,000 is very much lower than the permeability of iron, yet at great flux-densities the mild steel is equally as good as, or even better than wrought iron. Being much cheaper, it has come very much into use for dynamo magnets and pole-cores. Though this material is known as mild steel[1] it is in reality much more allied to iron in its composition, as it contains only about 0·06 per cent. of carbon and is incapable of taking a temper. Some data are given in Table III. The facts that it can be cast and is soft to tool greatly facilitate the construction of dynamo frames of mild steel. *Mitis metal,* which is a sort of cast wrought iron, being a wrought iron rendered fluid by addition of a small percentage of aluminium, is, as the author has found, more magnetizable than cast iron, and not far inferior to the best wrought iron.

Any specimen of iron or steel, for which, in comparatively weak fields the permeability goes up to 3000 or 4000, and which has little retention of its magnetism, is called magnetically *soft*; while any specimen which only reaches a permeability of 100 to 400, and that in a fairly strong field, is called magnetically *hard*, and will exhibit great retentivity.

---

[1] For data upon mild steel and mitis metal, see G. Henrard, *La Lumière Électrique,* xxxiii. 595 ; Thompson, Knight and Bacon, *Amer. Inst. Elec. Engs.,* ix. June 7th, 1892. Ewing, *Proc. Inst. Civil Engs.,* cxxvi., 1896 ; Parshall, *ibid.*

Hammering, rolling, chilling, or any process which tends physically to harden iron will lessen its permeability, but the evil effects of such processes may be destroyed by raising the metal to a red heat and allowing it to cool very slowly. The effect of this annealing is shown in the curves.

The curve for cast iron varies a great deal with the quality. The permeability is generally decreased in proportion to the amount of carbon present in the combined state.

For an account of the various methods of measuring[1] the magnetic qualities of iron, and for detailed information as to the newest kinds of iron and magnet steel, see the author's treatise on *The Electromagnet.*

Sheet iron often shows very different qualities in different parts of the same sheet. According to Röhr,[2] parts near the edges of the sheet are often better annealed than parts from the middle. Repeated annealing tends to make any sample more homogeneous magnetically. The most homogeneous magnetic material hitherto produced is annealed cast steel.

---

[1] Consult also the following works:—

Ewing, J. A., various papers in the *Philosophical Transactions* of the Royal Society in the years 1885 to 1894. A full résumé is given in his book *Magnetic Induction in Iron and other Metals.* London, 1894.

Hopkinson, Dr. J., papers in the *Philosophical Transactions* of the Royal Society, 1885 to 1895. Those of chief importance are reprinted in his *Original Papers* (1901), vol. i.

Du Bois, H. J. G., *Magnetische Kreise, deren Theorie und Anwendungen.* Berlin, 1894.

Parshall, H. F., *Electric Generators*, London, 1900; also *Proc. Inst. Civil Engineers*, cxxvi. May 19, 1896.

Schmidt, Dr. E., *Die Magnetische Untersuchung des Eisens.* Halle, 1900.

Lamb, C. G., and Walker, M., *Journal Inst. Elec. Engineers*, xxx. 930, 1901. This paper describes a practical form of permeability-meter.

Drysdale, C.V., *ibid.*, xxxi. 283, 1902. In this paper there is given a method of determining the permeability of specimens of iron or steel in the lump, without reducing them to rods, rings or strips.

[2] *Elektrot. Zeitschr.*, xix. 712, 1898.

EFFECTS OF AIR-GAP IN MAGNETIC CIRCUIT.

All the preceding results refer exclusively to that which goes on in iron itself, the curves of magnetization referring to the magnetic materials only. But if there is an air-gap in the magnetic circuit, or a gap filled with any non-magnetic material such as copper, mica or paper, seeing that all these things possess a permeability that is equal to that of air (*i.e.* $\mu = 1$), it is evident that to force the same number of magnetic lines across a layer of such inferior permeability will necessitate an increase in the amount of magnetizing power that must be applied.

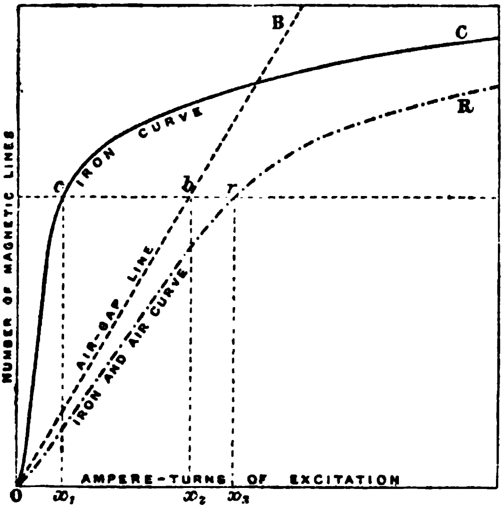


FIG. 51*a*.—CURVE OF MAGNETIZATION OF MAGNETIC CIRCUIT WITH AIR-GAP.

This is made plainer by reference to Fig. 51*a*, in which the curve O *c* C represents the relation between the number of magnetic lines in an iron bar and the number of ampere-turns of excitation ($= \mathcal{H}\, l \div 1{\cdot}257$) needed to force these magnetic lines through the iron. For example, to reach the height *c*, the excitation has to be of the value represented by the length $\mathrm{O}x_1$. On the same diagram the line O *b* B represents the relation between the magnetic flux across the air-gap and the ampere-turns required to force this flux across. If the gap were 1 cm. long, 0·795 ampere-turns of current would produce field $\mathcal{H} = \mathfrak{B} = 1$. In the present case the gap is supposed to be shorter than 1 cm., the line sloping up at such a slope that the length O x_2 represents the ampere-turns requisite to bring up the magnetic flux to *b*, which is at the same height on the scale as *c*. It is then easy to put the two things together, for the total amount of excitation required to force these magnetic lines through air and iron will (neglecting leakage) be the sum of the separate amounts. The point x_3 is chosen so that O x_3 is equal to the sum of O x_1, and O x_2, or that the distance of point *r* from the vertical axis is equal to the sum of the respective distances of *c* and *b*. If the same thing is done for a large number of corresponding points, the resultant curve O *r* R may be constructed from the two separate curves. It will be seen then that, in general, the presence of a gap in the magnetic circuit has the effect of causing the magnetic curve to rake over, *the initial slope being determined by the air-gap.*

Air-Gap Coefficients.—It is convenient in calculating to employ *gap-coefficients.* We have seen above that to drive magnetic lines, with a density of $\mathfrak{B} = 1$, along 1 cm. length of air, requires 0·795 (or approximately 0·8) ampere-turns. This number is, then, a coefficient which can be used for finding the ampere-turns needed for any other density or any other length. The number of ampere-turns X_g needed if the flux density is $\mathfrak{B}_g$ and the length across the gap l_g will be

$$X_g = 0{\cdot}8 \times \mathfrak{B}_g \times l_g.$$

If the density, is given in lines per square inch and the gap-length in inches, the coefficient will be 2·54 times smaller, and the equation becomes

$$X_g = 0{\cdot}3133 \times B_g \times l''_g;$$

where 0·3133 is the *gap-coefficient.*

EFFECT OF JOINTS.

Being now in a position to calculate the additional magnetizing power required for forcing magnetic lines across an air-gap, we are prepared to discuss a matter that has been so far neglected, namely, the effect of joints in the iron on the reluctance of the magnetic circuit.

Ewing [1] not only tried the effect of cutting and of facing up with true plane surfaces, but used different magnetizing forces, and also applied various external pressures to the joint. In Table IV. are summarised the results which Ewing found when his bar of wrought iron was cut across by section planes, first into two pieces, then into four, then into eight. The apparent permeability of the bar was reduced at every cut.

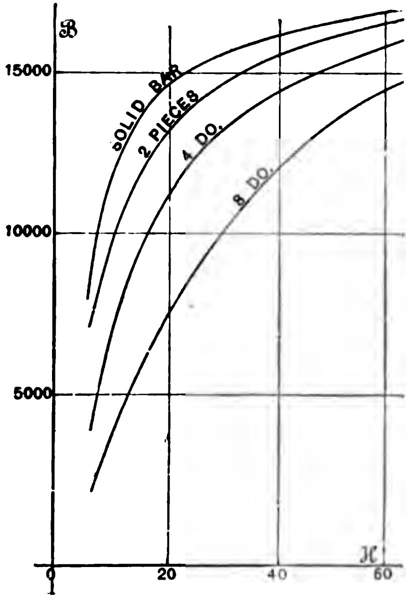


FIG. 52.—EWING'S CURVES FOR EFFECT OF JOINTS.

Suppose we are working with the magnetization of our iron pushed to about 16,000 lines to the sq. cm., referring to

---

[1] See *Philosophical Magazine*, Sept. 1888.

Table IV., we see that each joint across the iron offers as much reluctance as would an air-gap 0·0005 of an inch in thickness, or adds as much reluctance as if an additional layer of iron about $\frac{1}{6}$th of an inch thick had been added. With small magnetizing forces the effect of having a cut across the iron with a good surface on it is about the same as though you had introduced a layer of air $\frac{1}{600}$th of an inch thick, or as though you had added to the iron circuit about 1 inch of extra length. With large magnetizing forces, however, this disappears, probably because of the attraction of the two surfaces across that cut. The stress in the magnetic circuit, with high magnetic forces running up to 15,000 or 20,000 lines to the sq. cm., will of itself put on a pressure of 130 to 230 lbs. to the square inch, and so these resistances are considerably reduced; they come down in fact to about $\frac{1}{23}$rd of their initial value.

TABLE IV.—EFFECT ON JOINTS IN WROUGHT-IRON BAR (not compressed).

$\mathcal{H}$	$\mathcal{B}$				Mean thickness of equivalent air-spaces for one cut.		Thickness of iron of equivalent reluctance per cut.	
	Solid.	Cut in Two.	In Four.	In Eight.	Centimetres.	Inches.	Centimetres.	Inches.
7·5	8,500	6,900	4,809	2,600	0·0036	0·0014	4	1·57
15	13,400	11,550	8,900	5,500	0·0030	0·0012	2·53	1
30	15,350	14,550	12,940	9,800	0·0020	0·0008	1·10	0·433
50	16,400	15,950	15,000	13,300	0·0013	0·0005	0·43	0·169
70	17,100	16,840	16.120	15,200	0·0009	0·0004	0·22	0·087

The above results of Ewing's are further represented by the curves of magnetization drawn in Fig. 52. When the faces of a cut were carefully surfaced up to true planes, the disadvantageous effect of the cut was reduced considerably, and under the application of a heavy external pressure almost vanished.

EFFECTS OF HEAT.

When iron in a strong magnetic field is raised to a temperature above 600° C. it begins to lose its magnetic qualities, and at 780° C. they entirely disappear. At temperatures between 0° and 100° the effect of heat is so small that for all practical purposes it may be neglected.

RESIDUAL MAGNETISM.

It is well known that several kinds of magnetic materials —lodestone, steel, particularly hardened steel, and hard sorts of iron—exhibit residual magnetism after having been subjected to magnetic forces. It is also known that closed circuits of soft iron—even of the very softest—will exhibit a considerable amount of residual magnetism so long as the circuit which they constitute is unbroken.

Reference to Fig. 49 will show that when the magnetizing force $\mathcal{H}$ is gradually increased from zero to a high value, and is then gradually decreased to zero, the resulting internal magnetization $\mathcal{B}$ first increases to a maximum, and then decreases, but does not come back to zero. The curve descending from the maximum does not coincide with the ascending curve. In fact, when the magnetizing force has been entirely removed there remained (in this specimen) a residual magnetization of about 47,000 lines to the sq. in., or about 7300 lines per sq. cm. It has been proposed to give the name of the *remanence* to the number of lines to the sq. cm., that thus remain as the residual value of $\mathcal{B}$. To remove this *remanence*, a negative magnetizing force must be applied. Suppose enough magnetizing force has been used, the curve will descend and cut the horizontal axis at a point to the left of the origin ; and with greater negative magnetizing forces, the specimen will begin to be magnetized with magnetic lines running through it in the reversed direction. The particular value of the negative magnetizing force which is needed to bring the remanent magnetization to zero has been termed by Hopkinson *the coercive force.* In the specimen of wrought iron in question the coercive force (in C.G.S. measure) is about 2. The force thus required to deprive any specimen of its remanent magnetization may be taken as a measure of the tendency of iron of this particular quality to retain permanent magnetism. Hard kinds of iron and steel always show more coercive force than soft kinds of iron. For example, whilst that of soft wrought iron is about 2, that of hard steel may be as much as 70, or even more.

HYSTERESIS.

Professor Ewing, who has particularly studied the residual effects exhibited by various qualities of iron and steel, has given the name of *hysteresis* to this tendency of the effects to lag, in phase, behind the causes that produce them. The appropriate mode of studying hysteresis is to subject the specimen to a complete cycle (or to a number of successive cycles, of magnetizing forces. For example, let the magnetizing force begin at zero, and increase to a high value, and then decrease back to zero, then reverse and increase to a high negative value, and finally return to zero. Such a cycle is given in Fig. 53, which is taken from Ewing's researches, and relates to a series of experiments made with a piece of annealed steel. The curve begins in the centre of the diagram and as $\mathcal{H}$ is increased positively, the curve rises at first concavely to the right, then turns over, and when $\mathcal{H} = 55$, $\mathfrak{B}$ has risen to a little over 14,000. When $\mathcal{H}$ is then reduced back to zero the curve turns back on itself, but does not fall as fast as it previously rose, for when $\mathcal{H}$ is reduced to 20, $\mathfrak{B}$ has gone down only to 12,000, and when $\mathcal{H} = 0$ the remanence is about 8500. If at this point $\mathcal{H}$ had been again increased to 55, $\mathfrak{B}$ would have run up again to 14,000. If, however, the magnetizing force is now reversed, and gradually increased from 0 to -55, the curve descends to the left, and cuts the horizontal axis at -16, which is therefore the value of the coercive force. On increasing the reversed magnetizing force to $\mathcal{H} = -55$, the reversed magnetization increases to the value $\mathfrak{B} = -14{,}000$ or a little more. Then when these reversed magnetizing forces are reduced to zero, the curve returns towards the right, crossing the vertical axis at $\mathfrak{B} = -8500$ (the negative remanence); and on re-reversing the magnetizing force it is found that when $\mathcal{H} = +16$, the magnetization is once more zero. After this point, increasing $\mathcal{H}$ causes the magnetization to run up very rapidly, not quite following its former track, but coming up as before to the apex, when $\mathcal{H}$ is raised to the same maximum of 55.

CYCLES OF MAGNETIZATION.

Such cycles of magnetization as that which has just been described, if carried out on any specimen of iron or steel, always yield curves that exhibit, like Fig. 53, an enclosed area or hysteresial loop. This fact has been shown by Warburg[1] and by Ewing[2] to possess a special significance; for the area enclosed is a measure of the work wasted, per unit of volume of the iron, in carrying the iron through a complete cycle of magnetizations. Just as the area traced out on the indicator-card of a steam engine is a measure of the heat performed by the engine, so in this magnetic cycle the area enclosed by the curve is a measure of the work transformed into (useless) heat.[3]

For the sake of comparison, a curve for wrought iron and one for steel are given side by side in Fig. 53. In all these cases the closed area represents the work which has been wasted or dissipated in subjecting the iron to these alternate magnetizing forces. The loop curve so traced out is, therefore, a measure of the amount of *hysteresis* in the specimen. In very soft iron, where the ascending and descending curves are close together, the enclosed area is small; and as a matter of fact, very little energy is dissipated in a cycle of magnetic operations. On the other hand, with hard iron, and particularly with steel, there is a great width between the curves, and there is great waste of energy. The energy lost per cycle depends not only upon the nature of the material but also upon the degree to which the magnetization is carried in each cycle—in fact upon the *amplitude* of the cycle. As the amplitude of the loss of energy per cycle is more than proportionally great, doubling B more than doubles the energy loss per cycle.

---

[1] *Wied. Ann.*, xiii. 141, 1881.

[2] *Proc. Roy. Soc.*, xxxi. 22, 1881; xxxiv. 39, 1884; and xxxv. 1, 1885; and *Phil. Trans.*, 1885, pt. ii. 523.

[3] The proofs of these matters are as follows. In a magnetic field of strength $\mathcal{H}$ it will require $\mathcal{H}$ units of work to move a unit of magnetism along a length of 1 centimetre against the magnetizing forces. Hence since there are 4π magnetic lines to each unit of magnetism, the work done in one complete cycle on a single cubic centimetre of the iron will be equal to $\frac{1}{4\pi}\int \mathcal{H}\, d\mathfrak{B}$. If $\mathcal{H}$ and $\mathfrak{B}$ are in C.G.S. units, the work will be given in ergs per cubic centimetre. Hence if this number is multiplied by the number of cycles per second and divided by 10^7, the result will express the number of watts of power wasted.

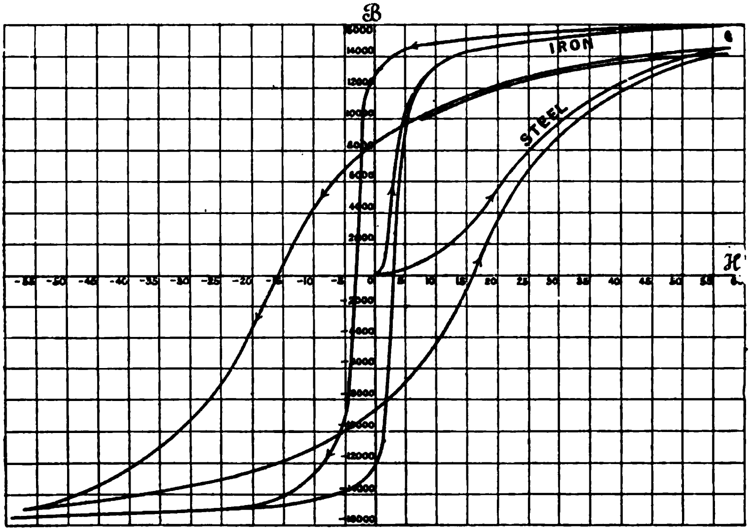


FIG. 53.—HYSTERESIS IN WROUGHT IRON AND IN STEEL.

Heat wasted in Cycles of Magnetization.—It has long been known that when iron is subjected to rapidly recurring magnetization and demagnetization, or to an alternating magnetization, it becomes hot. This heat so wasted in the iron is due to two causes—(1) hysteresis, (2) eddy-currents.

Hysteresis may be regarded as a species of magnetic fatigue which wastes energy at every reversal of the magnetization, as shown above, and occurs in all kinds of iron, but particularly in all *hard* kinds of iron and steel. To minimise this source of loss the cores of armatures, and the cores of transformers, must be made of material which has as low a hysteresis as possible.

Eddy-currents are currents induced in the substance of the iron core itself by the magnetic changes. They can be reduced indefinitely by laminating the cores, which are built up of thin sheets of iron or of a special soft steel; the usual thickness being from 25 to 40 mils thick, though in some cases core-sheets as thin as 15 mils (= about 0·6 millimetre) are employed.

Calculation of Heat-Waste in Iron Cores.—The energy lost per cycle depends not only upon the nature of the material but also upon the degree to which the magnetization is carried in each cycle—in fact upon the *amplitude* of the cycle. The loss of energy per cycle is more than proportionally great; doubling $\mathfrak{B}$ more than doubles the energy loss per cycle.

Mr. C. P. Steinmetz[1] has given the following law connecting the hysteresis loss h in ergs per cubic centimetre of iron per cycle and the flux-density $\mathfrak{B}$. He finds that

$$h = \eta \, \mathfrak{B}^{1\cdot6}$$

where η is a constant, called the hysteretic constant, depending upon the kind of iron. This law is true for cycles performed either slowly, or as rapidly as 200 per second. Table V. gives the hysteretic constant η for different materials[2] when ordinary frequencies are employed.

---

[1] *Amer. Inst. Elec. Engineers*, Jan. 19, 1892; *Electrician*, Feb. 12, 19 and 26, 1892. The exponent is not always exactly 1·6; it varies between 1·5 and 1·9.

[2] For particulars of Ewing's Magnetic Tester for measuring Hysteresis in sheet iron, see *Inst. Elec. Engineers*, April 25, 1895, also *Electrician*, xxxiv. 786. To reduce these values from ergs per cubic centimetre per cycle to the more ordinary value in watts per pound of iron at 100 cycles per second, multiply by the factor 0·000589. Barrett finds the values for Swedish charcoal iron, for Sankey's "Lohys" iron, and for aluminium-iron to be respectively 0·38, 0·32 and 0·23 watts per pound, with a maximum flux-density of 4000 lines per square centimetre.

TABLE V.—HYSTERETIC CONSTANTS FOR DIFFERENT MATERIALS.

Material.	Hysteretic Constant η.	Material.	Hysteretic Constant η.
Very soft iron wire . .	·002	Soft annealed cast iron .	·008
Very thin soft sheet iron .	·0024	Soft machine steel. . .	·0094
Thin good sheet iron . .	·003	Cast steel	·012
Thick sheet iron . . .	·0033	Cast iron	·016
Most ordinary sheet iron .	·004	Hardened cast steel . .	·025
Sankey's Lohys iron . .	·0012	Barrett's aluminium-iron	·00068

From experiments with actual transformer plates, at a frequency of n cycles per second, the hysteretic loss, in watts per cubic inch of iron, was found to be

$$W_h = 0{\cdot}83 \times \eta \times n \times \mathsf{B}^{1{\cdot}6} \times 10^{-7}.$$

In Fig. 54 there have been plotted the hysteresis losses in watts per pound of iron, at a frequency of 30 cycles per second, for different values of the flux-density (in British measure). The iron is here taken to be of an ordinary good quality.

Similarly, Fig. 55 gives in the form of a graph the losses, by hysteresis, in watts *per cubic inch* of *laminated iron*, such as is used in armature cores; the curve in this case being plotted for *one* cycle per second, the corresponding flux-densities being given per square inch.

Example.—Find the power wasted by hysteresis in the core-body of the 8-pole dynamo, page 563, assuming B = 65,000, the total volume of the iron being 16,320 cub. inches, and the frequency of the reversals 10 cycles per second, and the hysteretic constant = 0·002. Reference to Fig. 54 shows that the waste will be 0·008 watts per cubic inch per cycle per second. Therefore the power wasted will be 0·008 × 16,320 × 10 = 1305·6 watts.

Table VI. gives the number of watts wasted by hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

To facilitate calculations, Table VII. gives the number of watts wasted per cubic inch per cycle for three different values of the hysteretic constant.

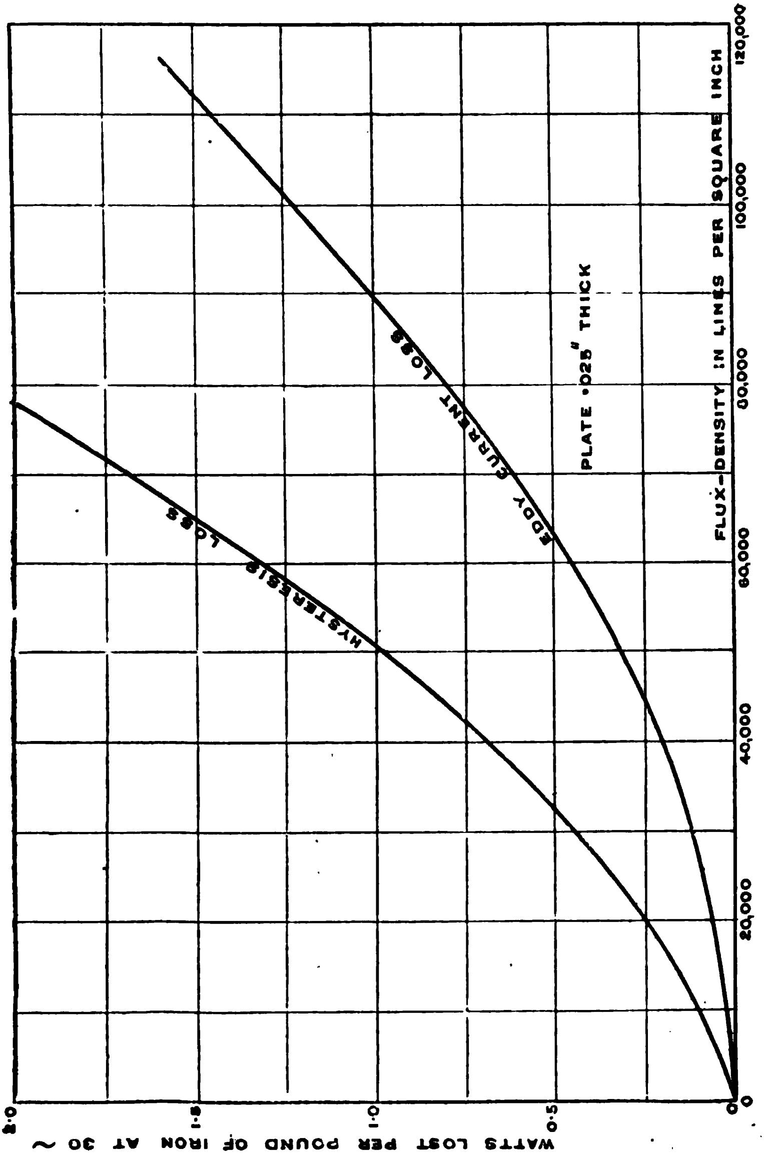


FIG. 54.—CURVES OF WASTE OF POWER IN MAGNETIZATION OF IRON.

TABLE VI.—WASTE OF POWER BY HYSTERESIS.

𝔅 Per square centimetre.	B Per square inch.	Watts wasted per cubic inch at 1 cycle per second.	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	0·0023	40	400
5,000	32,250	0·0033	57·5	575
6,000	38,700	0·0043	75	750
7,000	45,150	0·0053	92·5	925
8,000	51,600	0·0064	111	1110
10,000	64,500	0·0090	156	1560
12,000	77,400	0·0119	206	2060
14,000	90,300	0·0151	262	2620
16,000	103,200	0·0186	324	3240
17,000	109,650	0·0228	394	3940
18,000	116,100	0·0282	487	4870

TABLE VII.

Lines per square inch.	Watts wasted per cubic inch of iron per cycle per second.		
B	$\eta = 0\cdot002$.	$\eta = 0\cdot003$.	$\eta = 0\cdot004$.
40,000	0·003829	0·005767	0·007658
50,000	0·005478	0·008280	0·010956
60,000	0·007320	0·011080	0·014640
70,000	0·009345	0·014090	0·018690
80,000	0·011586	0·017455	0·023172
90,000	0·013993	0·021082	0·027986
100,000	0·016666	0·025000	0·033333
110,000	0·019322	0·029100	0·038644
120,000	0·022094	0·033425	0·044188
130,000	0·025248	0·038025	0·050496
140,000	0·028386	0·042750	0·056772

These values are plotted in the curves of Fig. 55. For other frequencies the values must be multiplied *simply by the frequency.*

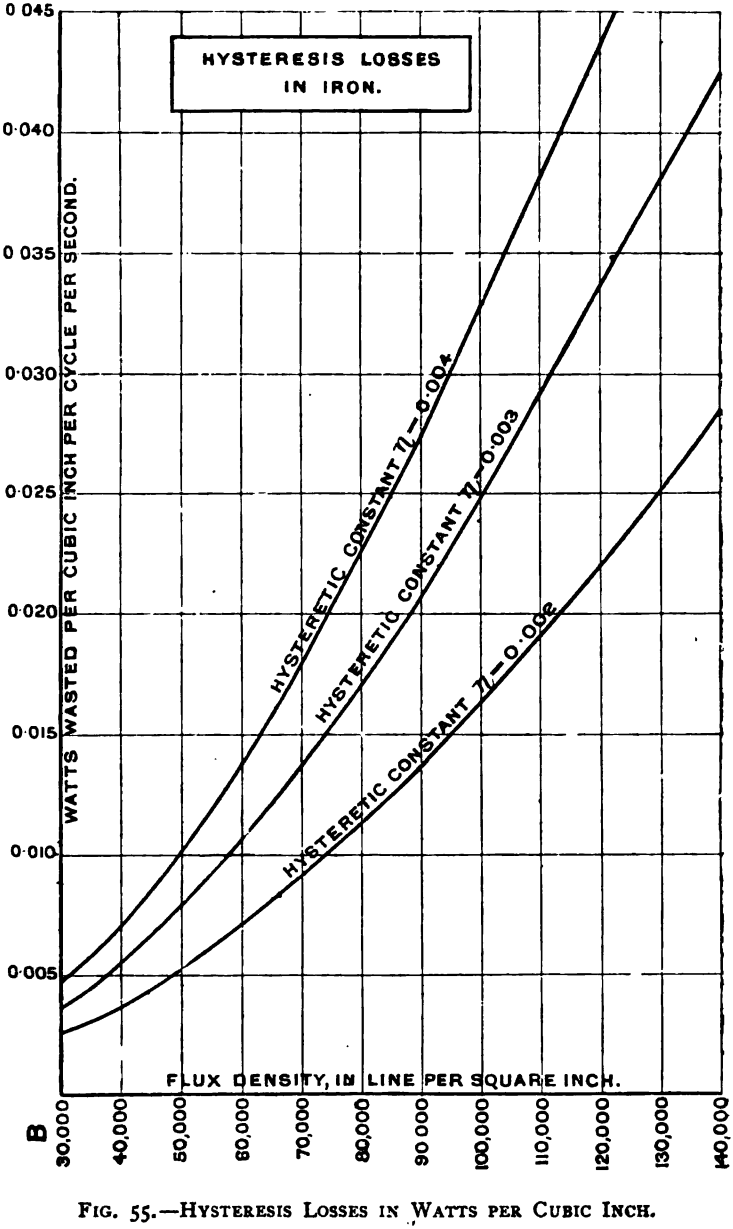


FIG. 55.—HYSTERESIS LOSSES IN WATTS PER CUBIC INCH.

Besides the hysteretic loss in iron plates, there is also a loss due to *eddy-currents* in the iron. This loss varies as the square of the thickness of the iron, the square of the frequency, and the square of the flux-density. There has been obtained by calculation the formula

$$W_e = 40{\cdot}64 \times t^2\, B^2\, n^2 \times 10^{-12},$$

W_e being the loss in watts per cubic inch of core made up of the strip, and t being the thickness of the strip in inches.

TABLE VIII.—Waste of Power by Eddy-Currents.

B	Eddy-current loss in watts per cubic inch, at 1 cycle per sec.			
	t = 10 mils	t = 20 mils	t = 40 mils	t = 60 mils
40,000	0·000006	0·000026	0·000104	0·000234
50,000	0·000010	0·000040	0·000162	0·000366
60,000	0·000015	0·000058	0·000234	0·000527
70,000	0·000020	0·000079	0·000318	0·000717
80,000	0·000025	0·000104	0·000416	0·000935
90,000	0·000033	0·000132	0·000526	0·001185
100,000	0·000041	0·000162	0·000650	0·001463
110,000	0·000049	0·000196	0·000787	0·001770
120,000	0·000058	0·000234	0·000936	0·002107
130,000	0·000068	0·000275	0·001099	0·002490
140,000	0·000080	0·000318	0·001275	0·002867

Thus we have the total loss in watts per cubic inch, due to both hysteresis and eddy currents—

$$W = 0{\cdot}83\, \eta\, n\, B^{1{\cdot}6} \times 10^{-7} + 40{\cdot}64\, t^2\, B^2\, n^2 \times 10^{-12}.$$

This has been found to agree very closely with practice.

In order to adapt the data to British measures, and to facilitate computation, Table VIII. has been prepared, showing the values of the eddy-current losses in sheet iron of four different thicknesses, with a frequency of one cycle per second. The values for other frequencies will require to be multiplied by the *square of the frequency.*

These figures are graphically plotted for reference in Fig. 56.

Example.—Find the number of watts wasted by eddy-currents in the armature core-body (not including teeth) of the 8-pole dynamo described on p. 563. Taking B = 65,000 lines per square inch, the

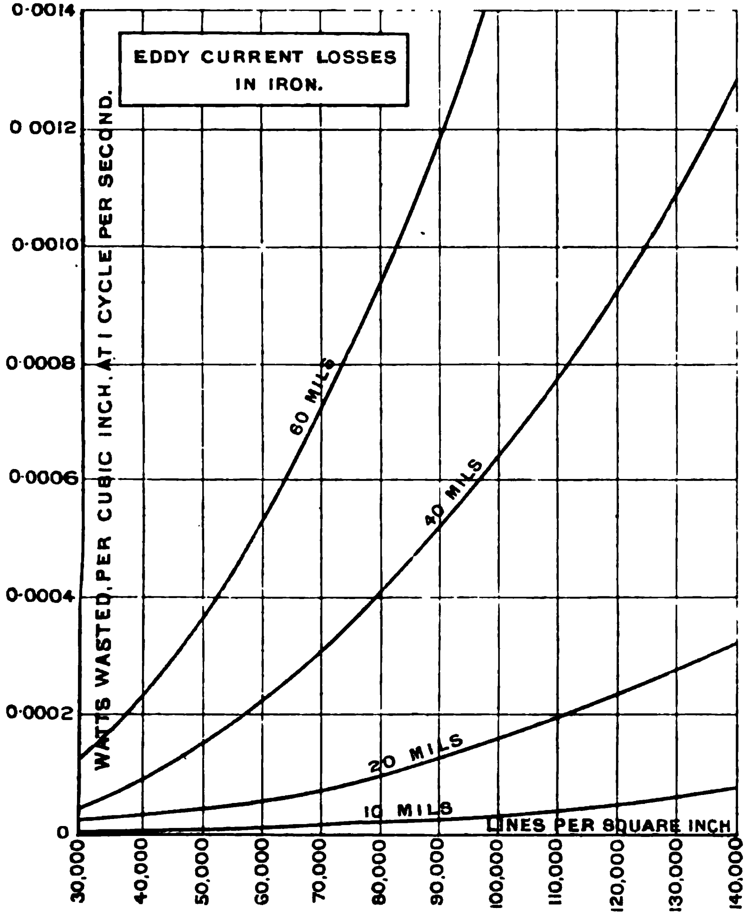


FIG. 56.—EDDY-CURRENT LOSSES IN SHEET IRON.

frequency 10 cycles per second, the thickness of the core-disks as 40 mils, and the number of net cubic inches of iron as 16,320, we proceed as follows. Referring to the curves of Fig. 56, we pick out the curve for 40-mil iron, and follow it up to opposite the value of 65,000, at which point we read off on the other scale the value 0·000275 as the number of watts per cubic inch at a frequency of 1 cycle per second. Then multiplying up by the square of the frequency, and by the number of cubic inches, we find as the total eddy-current waste, 449 watts. Had we taken core-disks of half the thickness this waste would have been reduced to 112 watts.

Examples of calculation of the waste of power by eddy-currents and hysteresis in the iron—usually called, for brevity, *the iron-losses*—in the armatures of continuous-current dynamos will be found in Chapter XIX.

Ewing has shown that vibration tends to destroy residual effects. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

Rotational Hysteresis.—When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found[1] the losses by hysteresis to be somewhat smaller in the former case than in the latter. Baily[2] found the losses, for a rotating density lower than $\mathfrak{B} =$ 15,000, to be slightly lower than is the case for alternating fields; but in stronger fields the rotational losses diminished after that point, and became nearly zero when $\mathfrak{B} = 20{,}000$. Dina[3] has recently re-examined the latter result.

Retardation of Magnetization.—It has long been known that in solid cores of electromagnets the rise and fall of the magnetism is retarded by eddy-currents in the iron, the outside part of the iron becoming magnetized first when the current is turned on; whilst the magnetism of the inner parts grows up later as the eddy-currents in the outer part die away. There is thus a regular penetration or propagation of the magnetism from the outer to the inner parts of the core. When the magnetizing-current is cut off, the inner part is the last to lose its magnetism. In large dynamos many minutes may elapse before the magnetism attains its maximum. For this reason the author pronounced it useless to put a compound winding upon certain dynamos with large solid bipolar electro-magnets for use as electric railway generators. Hopkinson[1] showed that the retardation varies as the square of the linear dimensions.

---

[1] See also Ewing in *Electrician*, xxvii. 602, 1891.

[2] *Phil. Trans.*, clxxxvii. 715, 1896.

[3] *Elektrot. Zeitschrift*, xxiii. 43, 1902; and xxiv. 674, 1903.

Magnetic Dampers.—If a magnetic flux, whether in air or in iron, be surrounded by a closed conductor such as a copper ring or tube, or a copper wire coil the ends of which are united together to form a closed circuit, it is impossible either to increase or to diminish this magnetic flux without setting up induced currents in the surrounding conductor; and these induced currents always tend to oppose, and therefore to delay the change of the flux. Hence, it is possible to protect any magnet pole against sudden changes in its magnetism by the simple device of surrounding it with a solid coil or circuit of copper to act as a *magnetic damper.* For this end Brush, in 1878, surrounded the limbs of his field-magnets with a copper tube. In recent times Hutin and Leblanc have proposed a device called an *amortisseur* (i.e. a *damper*) to prevent distortions of the magnetic field under the poles. For similar reasons the Westinghouse Co. inserts copper dampers between the pole-tips of its alternators and converters. A copper ring round a pole may thus prevent rapid changes in the enclosed flux, but cannot prevent distortion within the enclosed space from one part of the pole-face to another. To prevent this, or lessen it, one or more copper bars must be inserted across the pole-face and short-circuited together by outer bands. As induced currents can be set up in solid iron or steel as well as in copper, it follows that solid steel pole-shoes to some extent serve the same purpose as magnetic dampers, though less effectively than an amortisseur.

Magnetic Creeping.—Another kind of after-effect was discovered by Ewing, and named by him "viscous hysteresis." This is the name given to the gradual creeping up of the magnetization when a magnetic force is applied with absolute steadiness to a piece of iron. This gradual creeping may go on for half-an-hour or more, and amount to several per cent. of the total magnetization. This is a true, but slow, magnetic lag, and must not be confounded either with the lag of phase discussed already under the name hysteresis, or with the apparent lag due to the retardation of the magnetizing current resulting from self-induction, or with the apparent lag observable in unlaminated iron cores due to eddy-currents circulating in the mass of the iron itself.

---

[1] *Journ. Inst. Elec. Engineers,* Feb. 1895, and *Phil. Trans.,* 1895.

Slow Changes in the Magnetic Properties of Iron.—When iron is magnetized for a long time by rapidly alternating currents, its magnetic properties undergo a slight change, so that the amount of energy absorbed in carrying it through a given magnetic cycle is increased. This effect has been observed in connection with the working of transformers on alternate-current systems, and is due to a physical change in the iron, which affects its permeability or its hysteresis loss, or both. Whether the change is due directly to the continual reversal of magnetization or whether it is a secondary effect caused by the heating, and by the compression that takes place with the expansion of the iron through heat, is not certainly established, but a series of experiments carried out by Mr. W. M. Mordey,[1] point to the latter cause as being sufficient to account for the phenomenon.

Magnetic Circuit Calculations.—The remainder of the present chapter is chiefly of historical interest, the methods of calculation therein contained being now superseded. The reader will find the modern method fully set forth in Chapter VI., page 141.

Knowing the magnetic properties of the materials with which we have to deal, we are in a position to calculate the number of ampere-turns necessary to produce the desired flux in the magnetic circuit of a dynamo of any given shape and dimensions. The magnetomotive-force M gilberts, which is equal to 1·257 the ampere-turns C S, depends upon the reluctance R of the circuit, and the amount of flux N required. We in fact have the general equation

---

[1] *Proc. Roy. Soc.*, lvii. 1894; see also Allen, *Electrical World*, xli., 1048, June 1903, for some results obtained by the Bullock Co.

$$M = N \times R.$$

But as the total reluctance is made up of the reluctances of various parts of the circuit in series with one another, and which do not necessarily carry the same amount of flux, it is convenient to consider the parts separately. Referring to Fig. 57, which gives a diagrammatic view of the magnetic circuit of a bipolar dynamo, we have three parts, namely an iron armature-core, the two air-gaps, and the iron field-magnets.

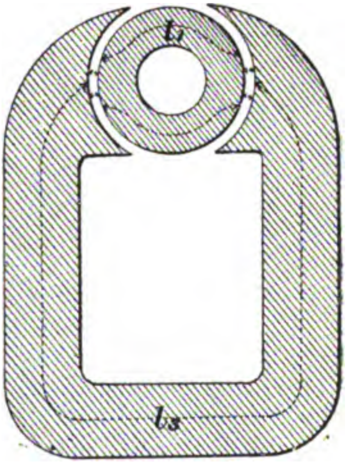


FIG. 57.

If the average length[1] of the path for the magnetic lines in the armature-core is denoted by l_1 and the average sectional area by A_1 and the permeability by μ_1, the reluctance of the cores will (see p. 82) be $\frac{l_1}{\mu_1 A_1}$. The total flux N through the armature divided by A_1 gives the flux-density $\mathfrak{B}$, so that μ_1 can be ascertained from the permeability curve of the material used. Then $\frac{N\,l_1}{\mu_1 A_1}$ gives the magnetomotive-force required to drive the flux through the armature core. Similarly $\frac{2\,N\,l_2}{A_2}$ (where l_2 and A_2 are the length and area respectively of one of the air-gaps) gives the magnetomotive-force required to drive the flux through the two air-gaps. The flux through the field-magnets is greater than that through the armature, owing to magnetic leakage. As will be seen below, we are able to express the average flux through the field-magnet in the form ν N, where ν is a number (generally about 1·3) which can be ascertained from the shape of the magnet (see p. 137). The symbol ν here stands for the *dispersion ratio*, or coefficient of magnetic leakage (see page 131 below). Having found the permeability μ_3 of the material of the field-magnet when carrying the flux ν N through the area A_3, we can write $\frac{\nu N l_3}{\mu_3 A_3}$ for the magnetomotive-force required for this part of the circuit. Then the total ampere-turns required will be

---

[1] For an example in the estimation of these lengths and areas, see page 148.

$$S\,C = \frac{M}{1 \cdot 257} = \frac{N}{1 \cdot 257}\left\{\frac{l_1}{\mu_1 A_1} + \frac{2\,l_2}{A_2} + \frac{\nu\,l_3}{\mu_3 A_3}\right\}.$$

This method of calculation is substantially that proposed independently in 1886 by Drs. J. and E. Hopkinson, and by Mr. Kapp. But the Hopkinsons went much further in their investigation. They plotted a separate curve for the relation between the magnetomotive-force and the flux for each separate part of the magnetic circuit, and then summed up the separate curves so as to obtain a final resultant characteristic curve. This is done first on the assumption that there is no magnetic dispersion; and after a first approximation has thus been obtained, the theoretical result is compared with the actual result of experiment, thereby affording a means of estimating the corrections that must be introduced.

As a matter of fact, the Hopkinsons stated their formula a little more generally. Instead of assuming the existence of μ for the different parts, they contented themselves with saying that the flux-density in each part must be some function of the magnetic force acting in that part. Now, if there be a flux of N magnetic lines passing through area A square centimetres, the flux-density $\mathfrak{B}$ will be equal to N/A. Accordingly, we may write for the magnetomotive-force acting in the armature part of the magnetic circuit $f\left(\frac{N_1}{A_1}\right) \times l_1$, which "function" may be examined and plotted out as a curve. In fact the curves of magnetization, such as are given on p. 82, are nothing else than curves which show the relation between the magnetizing forces and the amount of magnetism they induce. There will be a similar expression $f\left(\frac{N_3}{A_3}\right) \times l_3$ for the magnetomotive-force that acts in the field-magnet part, whilst for the gaps the magnetomotive-force is simply $\frac{N_2}{A_2} \times 2\,l_2$; for the function for air $= 1$. The whole or integral magnetizing force will be got by adding together the separate terms

$$l_1 f\left(\frac{N_1}{A_1}\right) + 2\,l_2\frac{N_2}{A_2} + l_3 f\left(\frac{N_3}{A}\right) = 4\,\pi\,S\,C \div 10.$$

This mode of stating the matter has the following advantages:—(1) The use of the function of which the value is to be found by reference to a curve or tabulated set of observations (such as those given in the preceding chapters, instead of merely using the symbol μ, makes the expression more general; (2) the separate terms being differently affected by leakage of the magnetic lines, it is easy to apply corrections separately.

If then we plot out, separately, curves for each of the three terms, so as to show separately the numbers of ampere-turns required to drive different amounts of magnetic flux through each of the separate parts of the circuit, we may then combine them in a resultant curve. Having in this way built up a curve characteristic of the magnetization, the Hopkinsons then proceeded to correct it by considering the dispersion. They found that in the dynamo experimented upon (an Edison-Hopkinson) only about three-fourths of the magnetic lines created in the field-magnet actually passed through the armature-core, the rest leaking across either between the pole-pieces through the air or the bed-plate, or else turning back from the pole-pieces, to the yoke at the top. Experiment gave for the ratio of the magnetic flux at a point half-way up the upright iron cores to the flux through the armature the value $\nu = 1 \cdot 32$. Then in the particular dynamo experimented on there was a yoke at the top through which the length of (curved) path was l_4, and which had cross-section A_4. There were also solid pole-pieces, for which the corresponding quantities were called l_5 and A_5. Inserting these additional matters into the equation, it now becomes

$$l_1 f\left(\frac{N}{A_1}\right) + 2\, l_2 \frac{N}{A_2} + l_3 f\left(\frac{\nu N}{A_3}\right) + l_4 f\left(\frac{\nu N}{A_4}\right) + 2\, l_5 f\left(\frac{N}{A_5}\right)$$

$$= 4\,\pi\, S\, C \div 10.$$

There are now five terms to be calculated, giving five curves (Fig. 58). Moreover, as is well known, with descending magnetizing forces the curve of magnetization is different from the curve with ascending magnetizing forces. Fig. 58, which is taken from the Hopkinsons' paper, shows how they plotted out both for ascending and descending magnetizations the five curves. Of these, A relates to the armature, B to the two interstitial gaps, C to the field-magnet cores, G to the yoke, and H to the two pole-pieces. To obtain the resultant curve the abscissæ at any particular level must be added together. For example: for a flux of 12 millions of magnetic lines, the air-gaps (curve B) required about 17,500 ampere-turns, the magnet-cores (curve C) 5000, the yoke (curve G) about 1000, and the armature (curve A) about 300, making a total of 23,800, which is accordingly plotted off to the right. The resultant curve is swept through the points so calculated. The resultant ascending and descending curves are both shown. They agree remarkably well with

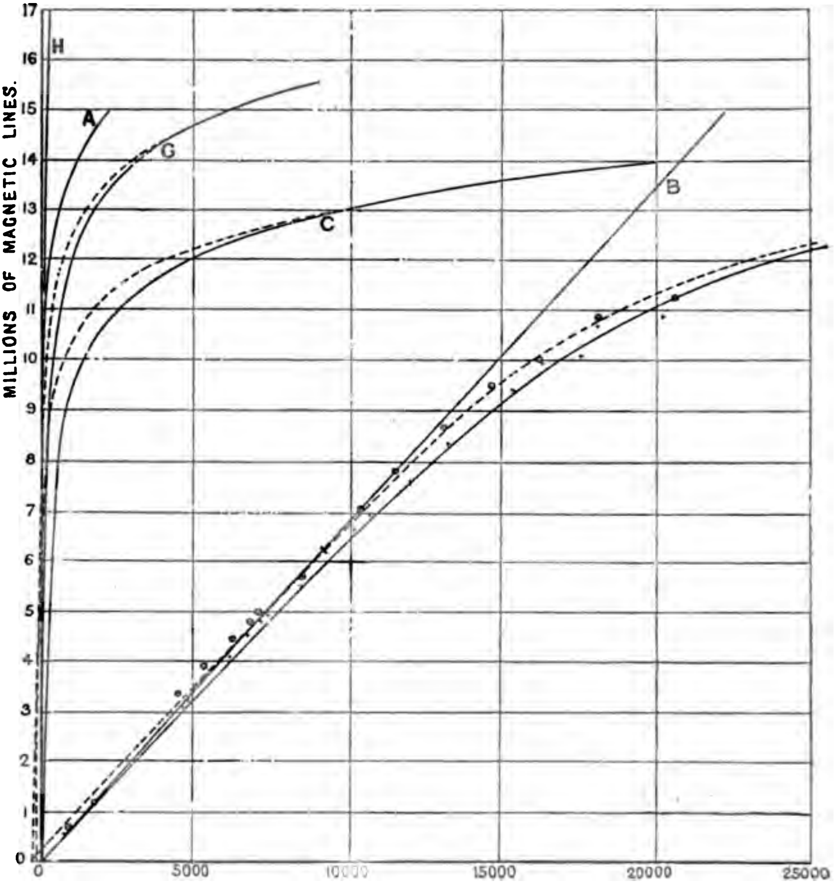


FIG. 58.—HOPKINSON'S PREDETERMINED NO-LOAD CHARACTERISTIC OR SATURATION-CURVE.

the crosses and points which were plotted out from actual experiment. The dotted curves and the crosses surrounded with circles relate to descending magnetizations. The student should not fail to consult the original memoir: it has been reprinted in the volume of Hopkinson's *Original Papers* (Cambridge, 1901).

The position of the magnetizing coils on the magnetic circuit is a matter of some importance. The electric and magnetic circuits being interlinked wherever the coils are placed they will exert the same total magnetomotive-force, but it is well, in view of the occurrence of magnetic leakage, to place the coils as near as possible to that part of the magnetic circuit where the magnetomotive-force is required. As has been pointed out above (p. 80), when there are several coils, their magnetomotive-forces will only be added together if they are interlinked with the same magnetic circuit; and therefore when a double magnetic circuit is employed (as in a dynamo of the Manchester type, for instance), each branch of the circuit requires to be wound with sufficient ampere-turns to give the required difference of magnetic potential between the poles. Thus, other things being equal, twice as much power is wasted in the field-magnet. However, as the girth of each branch is less than the girth of a single circuit, it is not necessary to use quite twice as much copper in winding in order to have the same loss per coil. In cases where several magnetic circuits are required, as in a multipolar field-magnet, it is sometimes convenient to have only one magnetizing coil and interlink all the magnetic circuits with it; such an arrangement is shown in Fig. 67. It would even be possible to wind the magnetic circuit several times round the electric circuit.

APPROXIMATE FORMULÆ FOR THE LAW OF THE ELECTRO-MAGNET.

Before the discovery of the law of the magnetic circuit, many attempts were made to find a working formula to express the amount of magnetism which is produced in a given electromagnet by an exciting current of any particular value. Of these an elaborate account is given in the second and third editions of this book. As they are not now used in dynamo designing, they may be very briefly dismissed.

The earliest suggestions of Lenz and Jacobi was a simple proportion between the exciting current and the magnetism produced. This is equivalent to saying that the curve of magnetization is a straight line sloping upwards from the origin. Joule showed that this law was not true; that with sufficient magnetizing power saturation set in. Müller (followed by Von Waltenhofen, Kapp and others) proposed an arc-tangent formula; suggesting that if the exciting current be represented by the length of a straight line drawn as a tangent to a circle, then the arc which it subtends will represent the amount of magnetism which results. This gives a saturation limit, but fails to represent the facts in the earlier stages of magnetization. Lamont, from theoretical considerations, proposed an exponential formula, from which he deduced an approximate expression equivalent to the statement that the permeability is at all stages proportional to the difference between the actual amount of magnetism and its possible maximum amount. Lamont's formula was revived by Frölich,[1] and largely used in various forms by various writers, including the author of this book. Let us make the supposition that the magnetic flux N will have at complete saturation a maximum value $\overline{\mathsf{N}}$, and that the magnetizability of the magnet at any stage is proportional to the room left for magnetic lines, that is to $\overline{\mathsf{N}} - \mathsf{N}$. Now, writing S for the number of spirals and C for the current flowing in them, we get C S for the ampere-turns of exciting power, and $\mathsf{N} \div \mathrm{C\,S}$ will be the ratio of magnetism to magnetizing power or magnetizability. We may then write

$$\frac{\mathsf{N}}{\mathrm{C\,S}} = \frac{\overline{\mathsf{N}} - \mathsf{N}}{h},$$

where h is a constant of the particular electromagnet. By simple transformation this equation becomes

$$\mathsf{N} = \overline{\mathsf{N}}\,\frac{\mathrm{C\,S}}{\mathrm{C\,S} + h},$$

and it is clear that the meaning of h is: that particular number of ampere-turns which will reduce the magnetizability to half its initial value, or will bring up the magnetism to half-saturation.

This number of ampere-turns the author named the *diacritical* number, and the number producing half-saturation he called the *diacritical* current. Dr. Frölich has independently made use of this conception, and has applied it in his formula for dynamos. The argument is his; the notation here used is, however, the author's.

This formula, though it does not take into account the difference between ascending and descending magnetizations, is quite good enough to serve as a first approximation, and is therefore useful. As pointed out by Fleming[2] and by Kennelly,[3] the justification of it is to be found in the circumstance that the reluctivity (or reciprocal of the permeability) is very nearly a simple linear function of $\mathfrak{H}$.

---

[1] *Elektrotechnische Zeitschrift*, pp. 90, 139, 170, 1881, and p. 73, 1882. See also Dr. Frölich's book, *Die dynamoelektrische Maschinen*, Berlin, 1886.

[2] *Journ. Inst. Elec. Engineers*, xv. 570, 1886.

[3] *Electrical World*, xvii. 358, 1891.

CHAPTER V.

FORMS OF FIELD-MAGNETS.

WITH the principle of the magnetic circuit to guide him, the reader will have little difficulty in judging of the relative value of various designs of field-magnets and field-frames ; for he will remember that the magnetic circuit of highest permeability will have the most compact form, greatest cross-section, softest material, and fewest joints. In many cases, however, the structure which acts as magnet has also to do duty as a framework, involving other considerations. Theoretically it is better that the field-magnet of a simple 2-pole machine should be constituted of a single magnetic circuit than of two (see p. 113) ; though for practical structural reasons the double circuit is preferable in some cases. A double circuit, that is to say one resembling No. 3 or No. 8 of the accompanying Fig. 59, has in general the advantages that it affords a more stable framework, and that its magnetic field is less liable to distortion than that of No. 2. These points should be borne in mind in considering the forms depicted in the accompanying figures. No. 1 of these illustrations shows the type adopted by Wilde for use with the shuttle-wound armature of Siemens. Two slabs of iron are connected at the top by a yoke, and are bolted below to two massive pole-pieces. There are four joints in the magnetic circuit in addition to the armature gaps, and the yoke is drawn too thin. No. 2 shows the form adopted in the Edison dynamos (standard bipolar pattern). The upright cores are stout cylinders. The yoke is of immense thickness ; the pole-pieces are massive, but their lower corners are cut away. There are as many joints as in Wilde's form ; but such a circuit should possess a far higher magnetic conductivity than Wilde's, owing to the greater cross-section

One difficulty with such single circuit forms is how to mount them upon a suitable bed-plate. If mounted on a bed-plate of iron, a considerable fraction of the magnetism will be short-circuited away from the armature, as has been shown in the

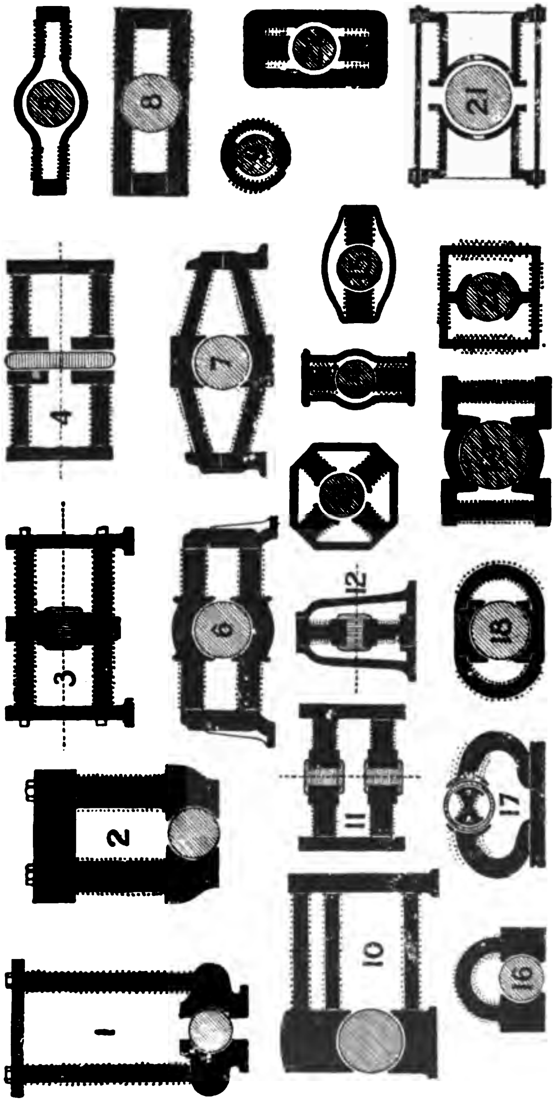


Fig. 59.—Typical Forms of Field-Magnets.

preceding chapter. In the larger form, No. 10, used at one time by Edison, this difficulty was only partially obviated by turning the magnets on one side. In modern "under-type" machines the field-frame is mounted away from the bed-plate upon a gun-metal or zinc foot-step.

A favourite type of field-magnet, having a double magnetic circuit with "consequent" poles, is represented in No. 3; it was introduced by Gramme. It may be looked upon as the combination of two such forms as No. 1, with common pole-pieces. Nos. 3 to 9 may be looked upon as modifications of a single fundamental idea. No. 4 gives the form used in the two-pole arc Brush dynamo (plan), the two magnetic circuits converging upon the ring armature. The diagram will serve equally for many forms of flat-ring machine; but in most of these the poles at the two flanks of the ring are joined by a common hollow pole-piece, embracing a portion of the periphery of the ring. No. 5 shows an early form of Siemens, with arched ribs of wrought iron, having consequent poles at the arch. The circuit is here of insufficient cross-section. No. 6 depicts a form adopted by Weston: and very similar forms have been used by Crompton, and by Paterson and Cooper. There is a better cross-section here. No. 7 is a form used by Bürgin and Crompton, and differs but slightly from the last. It has one advantage—that the number of joints in the circuit is reduced. No. 8 is a form used by Crompton, Kapp and others. No. 9 is the form adopted in the little Griscom motor. No. 18 is a further modification due to Kapp. No. 19, which also has consequent poles, was used by McTighe, by Joel, and by Hopkinson ("Manchester" dynamo), by Clark, Muirhead & Co. ("Westminster" dynamo), by C. E. L. Brown (Oerlikon), and in some of Sprague's motors; but with slight differences in proportions of the details. The main difference between No. 19 and No. 6 lies in the position selected for placing the coils, No. 19 requiring two, No. 6 four. No. 20, which is a design of Elwell and Parker, is a further modification of No. 3, and would be improved by having a greater cross-section. In No. 3 (Gramme), it is usual to cast the pole-pieces and end-plates, but to use wrought iron for the longitudinal cores. The requisite polar surface must be got by some means, and when the core was made thin, the two courses open were either to fasten upon the core a massive pole-piece (Nos. 1, 3, 4, 6, 7, 19, 20), or else to arch the core (No. 5) so that its lateral surface was available as a pole. Now, however, that it is known that massive cores are of advantage, the requisite polar surface can be obtained without adding any polar expansion or "piece," but by merely shaping the core to the requisite form (No. 8). This must not be regarded as a thinning of the magnet; for though mere reduction of cross-section at any part of the circuit would reduce the magnetic conductivity, reduction of the thickness for the purpose of bringing the armature more closely into the circuit will have quite the opposite effect. In fact the horizontal bars above and below the armature might be thinned away to nothing at their middle point, but for structural reasons. In all such forms of double magnetic circuit each half of the field-magnet may be regarded as having to furnish magnetic lines to its own half of the armature, Nos. 11 to 15 illustrate forms of field-magnet having *salient*, as distinguished from *consequent* poles. No. 11 is a double Gramme machine designed by Deprez. Nos. 12 and 13 are two of the innumerable patterns due to Gramme himself. These are both of cast iron; and it will be noticed that in No. 13 there are no joints, it being cast in one piece. No. 14 is a form used by Hochhausen, and is practically identical with No. 21, save in the position of the axis of rotation. The iron flanks of No. 14 tend to produce a certain short-circuiting of the magnetism by their proximity to the poles; and their sectional area is insufficient. No. 15, used by Van de Poele, is similar. No. 16 is the form used by the author in small motors, and is cast in one piece. The semicircular form adopted for the core was intended to reduce the magnetic circuit to a minimum length. No. 17 has salient poles reinforced by other electro-magnets within the armature. No. 21 shows in section the double tubular magnets of the Thomson-Houston dynamo, the spherical armature being placed, as in Nos. 12, 14, and 15, between two salient poles. There is a curious analogy between Nos. 21

and 19; but they entirely differ in the position of the coils. No. 22 is a design by Kapp, in which there are two salient

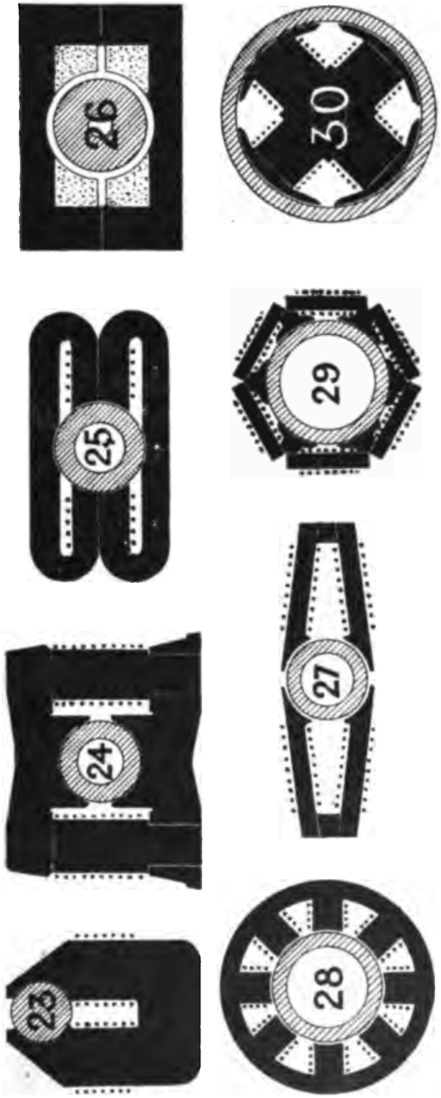
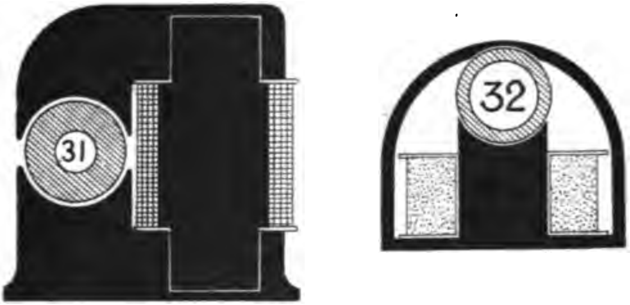


Fig. 60.—Typical Forms of Field-Magnets.

poles of similar polarity, and two consequent poles between them, one pair of coils sufficing to magnetize the whole quadruple circuit. This pattern has been much used for small machines by the Swiss engineers and by Kolben and Co. Almost identical forms have been employed by Rankine Kennedy ("iron-clad" dynamo), No. 25. Lahmeyer and Wenström employ iron-clad forms resembling No. 15. That of Wenström has for its yoke an external iron cylinder. No. 23, Fig. 60, with armature at the top, is known as the "over-type" of bipolar machines. It is an old form which was revived in 1884 by Gramme (" type supérieur "), by Kapp, by Siemens and by others. No. 24 is Brown's very massive form. No. 26 is designed by Professor George Forbes. The iron-work is in two halves; the coils, which are entirely enclosed, are so placed as to magnetize the armature directly, one coil occupying all the available space between the field-magnet and the upper half of the armature; the other the similar space around the lower half. No. 27 is a 4-pole form adopted by Elwell-Parker, and also by Crompton. No. 28 is a multipolar form, used by Wilde, Gramme and others, the poles which surround the ring being alternately of opposite sign. It was at first largely used for alternate-current machines such as those of Westinghouse, Mather and Platt (Hopkinson), and others, and is now almost universal for all large continuous current generators. In No. 22, a modification of this design by Thury, for use with a drum armature, the six inwardly-directed poles are magnetized by coils wound upon the external hexagonal frame. No. 30 is a sketch of a form introduced by



FIGS. 61, 62.—TYPICAL FORMS OF FIELD-MAGNETS.

Siemens and Halske, and also by Ganz, Fein and others, wherein an external ring rotates outside a very compact and substantial 4-pole electro-magnet. Similar machines, but with more than four internal poles, are largely used in Germany, for large central station machines.

Another form of field-magnet is shown in No. 31. This, which is a single horse-shoe with but one coil upon it, was a design by the author of this work early in 1886: it was used largely by Goolden and Co., by Greenwood and Batley, and other British makers. No. 32 represents also a machine requiring but one coil, and is of the iron-clad type. A pattern designed by Mordey for the Brush Company resembling No. 32, had an external iron cylinder to enclose the coil. In Fig. 73 is represented Lahmeyer's form, also with inward-pointing poles: like the preceding it belongs to the "iron-clad" type, the yoke of the magnet being exterior.

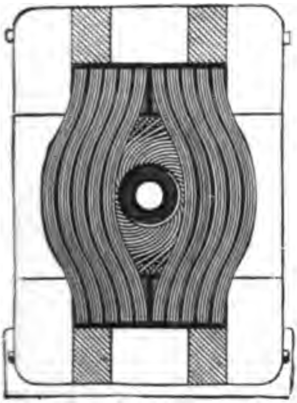


FIG. 63.
EICKEMEYER'S DYNAMO.

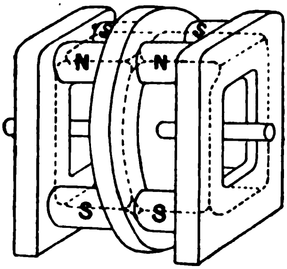


FIG. 64.
FOUR-POLE MAGNET (MORDEY).

Eickemeyer's dynamo (Fig. 63) realizes the suggestion of Forbes to place the magnetizing coils over the armature. The coils, which are separately wound on formers, fit into recesses between the upper and lower yokes and the inwardly projecting polar masses.

Fig. 64 represents a form of 4-pole field-magnet, formerly used by the Brush Company for their Victoria (Mordey) machines, having double magnetic circuits and consequent poles. The cores to receive the coils are of wrought iron, whilst the end frames and pole-pieces are cast. This should be contrasted with the form of 4-pole magnet, Fig. 65, designed in 1887 by Brown, and constructed by the Oerlikon works, for some large 300 horse-power machines for transmission of power. These are made entirely of cast iron, and have salient poles. The direction of the flux through these machines is indicated by dotted lines.

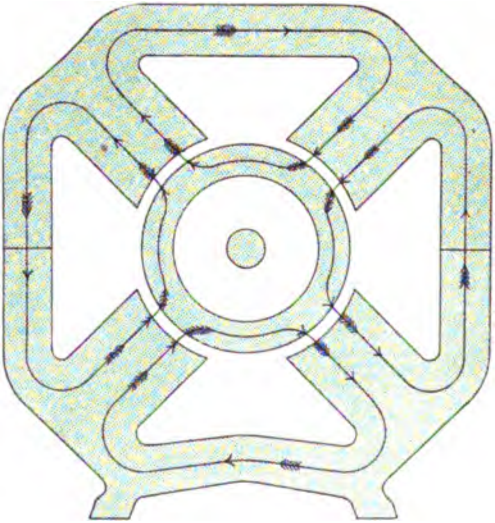


FIG. 65.—FOUR-POLE MAGNET (BROWN).

A typical form of magnet for alternate-current machines is Fig. 66, used by Siemens, Wilde, Ferranti and others, having two crowns of alternate poles facing one another.

In recent years a class of alternate-current machines has sprung up and met with considerable favour, having a single exciting bobbin common to many poles, this bobbin either being fixed or rotating with the field system. This form of *homopolar* construction, originally due to Mr. Mordey, was further developed by Brown, who introduced the form with imbricated poles or "claw-magnets." The idea has recently been extended by Mr. V. A. Fynn, who has designed a number of multipolar machines for continuous current upon this plan. One of these, an enclosed motor, is shown in Fig. 67, in which the single exciting coil is clearly visible owing to the upper half of the field frame having been removed. The field poles are "staggered," and on each side of the coil, as may be seen from the figure.

In the Lundell motor a similar device is employed to produce a two-pole field excited by a single oblique coil (Fig. 68).

Among such a multiplicity of designs one seeks for some indication as to the best. But the best for one purpose is not the best for all. Some designs are suitable for cast material; others for wrought iron; others again, such as Figs. 61 and 64, are expressly intended to be composite, having wrought cores for the bobbins and cast polar masses.

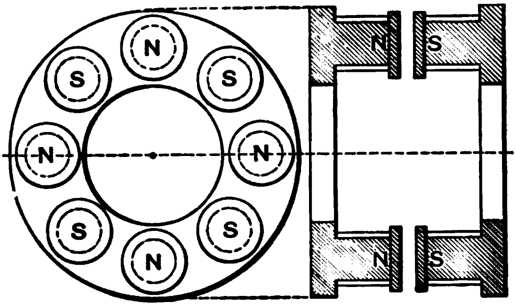


FIG. 66.—ALTERNATE-CURRENT FIELD-MAGNET.

It is desirable, where possible, to have the core upon which the coils are wound cylindrical, as that shape has the least perimeter for a given sectional area, and in consequence allows a saving in copper wire as well as making the winding simpler. In modern multipolar designs, both for continuous and alternate current, the employment of circular cores is rendered easy on account of the existing practice of constructing armatures whose axial length is short in comparison with their diameter. There is a tendency at the present time to make the wound core of a material of high permeability, such as cast steel, so that its perimeter can be reduced and a saving effected both

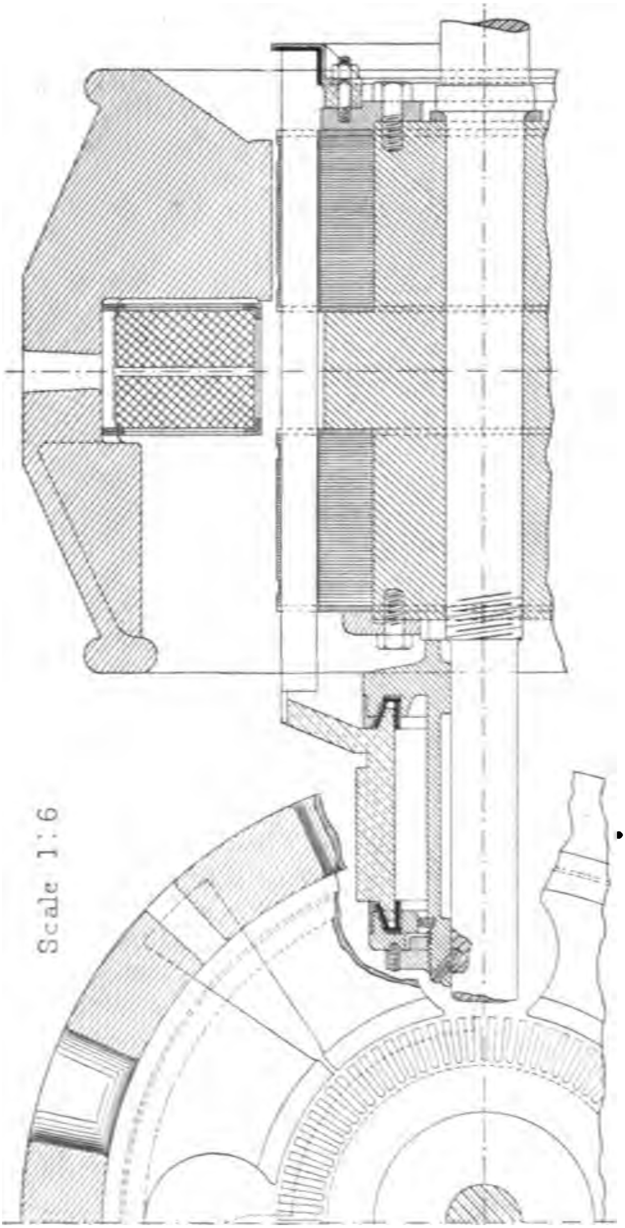


FIG. 67.—FIELD-MAGNET OF FYNN.

in iron and copper. As the exciting coils are generally wound on detachable reels, the shape of the field-magnet should permit of these being put off and on. For small machines a simple circuit is probably the best. For large machines it is found needful to multiply the number of poles: and for alternators, multipolar forms are necessary for obtaining a sufficiently frequent alternation of currents.

For facilitating comparison as to the weight of copper required by different shapes of field-core for equal ampere-turns, the following table gives the relative lengths of wire required to wind round various forms of section enclosing equal area; the area of the simple circular form being taken as unity, and allowance made for thickness of winding:—

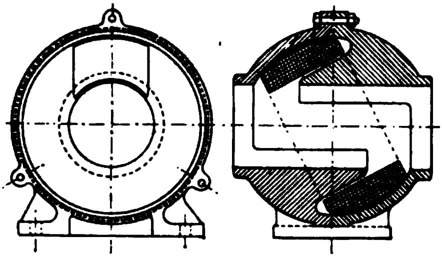


FIG. 68.—FIELD-MAGNET OF LUNDELL MOTOR.

Circle	3·54
Square	4·00
Rectangle, 2 : 1	4·24
Rectangle, 3 : 1	4·62
Rectangle, 10 : 1	6·91
Oblong made of one square between two semicircles	3·76
Oblong made of two squares between two semicircles	4·28
Two circles side by side	4·997
Two circles, but wire wound round both together	4·10
Three circles ,, ,, ,, each separately	6·13
Four circles ,, ,, ,, ,, ,, ,,	7·09

For pole-cores of elliptical section it is convenient to remember that the perimeter of an ellipse having major and minor axes *a* and *b* is approximately equal to that of a circle the diameter of which is $\frac{5}{4}$ of the arithmetical mean less $\frac{1}{4}$ of the geometrical mean between *a* and *b*.

Symmetry of Field-magnets.—It was pointed out on page 115, that in 2-pole single-circuit field-magnets the field is unsymmetrical. Forms with a double magnetic circuit such as Nos. 15 and 24 are preferable to those, such as Nos. 2, 23, and 31, with a single magnetic circuit, in all cases where there is likely to be much armature reaction. For in such forms as No. 23, the field is weaker under the two upper pole-tips than between the two lower ends of the pole-faces; in consequence there is a powerful attraction downward of the armature. Further, because of this inequality of field the cross-magnetizing force of the armature will produce, in the single-magnet

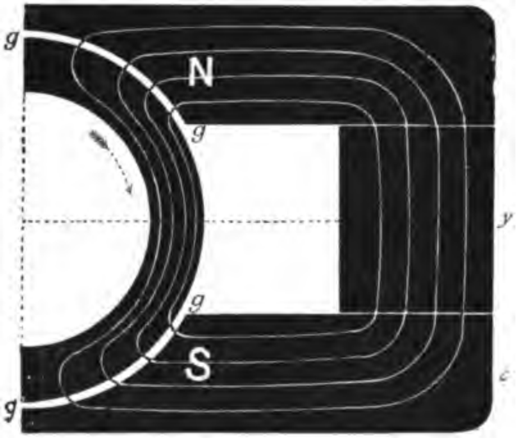


Fig. 69.—Half of a Double-magnetic Circuit Machine.

orms, an unsymmetrical distortion. As a consequence there is sure to be sparking at the brushes, which may however be partly remedied by setting one brush a little ahead of the other, that is, the brushes will not have equal angles between them. For large-load bipolar armatures, it is advisable not only to use double-magnets, but to separate their two halves by a distance-piece of brass.

In calculating those forms of field system which have double or multiple magnetic circuits, it is usual to simplify matters by considering one element of the whole, and making the calculations for it. Thus, for example, in Fig. 69, which depicts the half of such a machine as No. 8 of Fig. 59, it is sufficient to calculate the magnetic reluctances of half the machine in order to ascertain the number of ampere-turns that must be wound upon it; a similar number being wound upon the other half.

Forms of Pole-pieces.—A few continuous-current machines, and the majority of alternate-current generators, have no special polar-shoes: but most continuous-current machines are designed with an extended pole-piece or pole-shoe which covers a wider arc than the mere end of the pole-core would do. Great attention has been paid to the special shaping of these polar parts, which in some cases are constructed as separate shoes attached to the core. It is in fact found that upon the proper adaptation of these parts depends the satisfactory performance of the machine in sparkless running. Some account of these varieties of shape is to be found at the end of Chapter X.

The advantage of the extended size of pole-shoe is that it reduces the reluctance of the air-gap, thus enabling fewer exciting coils to be used. On the other hand, there is distinct advantage in having the pole-shoe itself well saturated. Hence to fulfil both conditions it ought either to be made of a less permeable material than the pole-core—for example of cast iron rather than of wrought iron or mild steel. Or if made of stampings of iron or soft steel it ought to be so designed that its inductive edges at least should be well saturated. It is well known that for satisfactory commutation at all loads without shift of brushes it is of advantage that there should be a relatively large number of ampere-turns of excitation applied in driving the flux across the gap and through the teeth. There is in reality no advantage in a wide gap for this purpose. It would be better to fill the gap as far as possible with highly saturated iron. Perforating the pole-faces (if of laminations) with closed slots and narrowing the gap to a minimum would yield good results: but they can be attained more cheaply in other ways. A machine with highly-saturated pole-shoes will regulate better than one not so highly saturated.

Forms of Yokes.—The yokes of almost all machines exceeding 20 kilowatts are now made as a ring from which the poles protrude inwardly. To secure stiffness, the section of the yoke is sometimes provided with external ribs. Fig. 70 gives a number of typical forms, of which A, B and C are suited for cast-iron yokes. The form C is that used in the Crocker-Wheeler multipolar machines; D is affected by Kolben and by the Oerlikon Co.; E by Mr. Parshall and by the General Electric Co. (Schenectady). Often the yokes are contracted in with a species of dimple behind the seats of the pole-cores, where

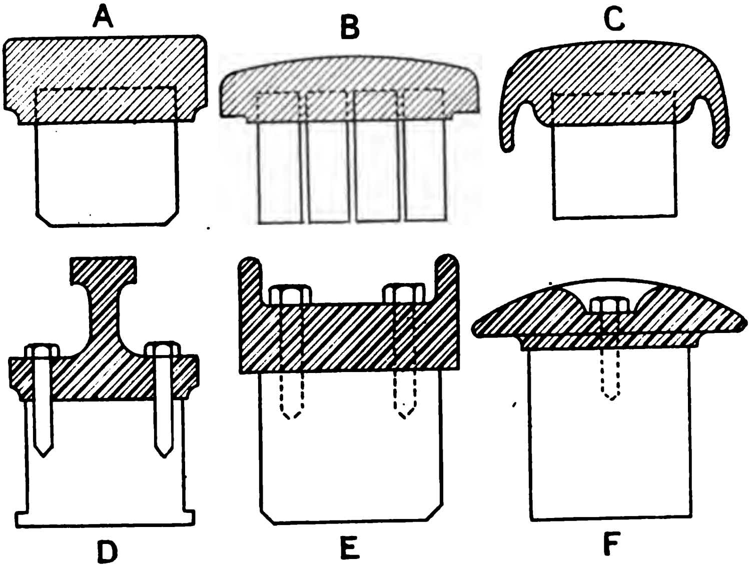


FIG. 70.—VARIOUS SECTIONS OF YOKES.

a great thickness of iron would serve no useful function, but these parts are sometimes stiffened with a wider rib as in Fig. 71 B. Where detachable pole-cores are employed the seating on the yoke is usually faced off flat to receive cast-steel cores: but if the pole-cores are made of stampings the seating is generally bored concentrically, and the stampings are often held up by a dove-tail bar inserted transversely. The author recommends as simpler a cylindrical bar as in Fig. 71 C. It is usual to employ two screws, or one screw and a steady-pin, rather than bolts, for securing the pole-cores to the yoke, in order that individual poles may be removed while the armature is in place.

Division of the Yoke.—To permit of inspection or repair of the armature, it must either be made removable longitudinally or else the yoke must be divided to permit of removal. A frequent plan is to divide the yoke across a horizontal diameter into an upper and a lower half, the lower being seated on, or cast in one with the bed-plate, while the upper is furnished with an eye-bolt or two eye-bolts to permit of raising it. The joints so admitted, even if carefully faced, and well bolted together, add a little reluctance to the magnetic circuits. If a 6-pole machine is thus built, with three poles on each half, it is certain that unless there is slightly more excitation wound on the 4 poles nearest the joints in the yoke, they will be slightly less strong than the other two poles. This effect of joints may be minimized by enlarging the area of contact, as is to be seen in so many examples in this book. In some cases the division of the yoke is made in a vertical plane, as in the case of the 8-pole metallurgical machine of Brown, Plate VII., and Fig. 403, p. 610.

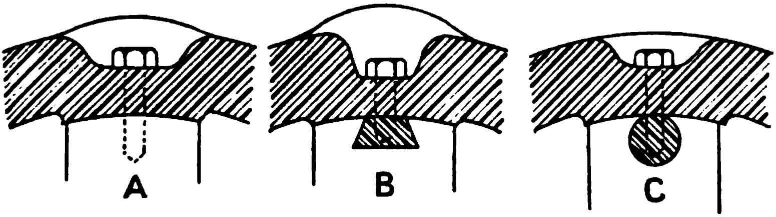


FIG. 71.—ATTACHMENTS OF POLE-CORES.

CHAPTER VI.

MAGNETIC CALCULATIONS AS APPLIED TO DYNAMO MACHINES.

BASED upon the fundamental magnetic principles already dealt with in Chapter IV., we now proceed to extend them to the case of the actual calculations as required in commercial designing. We have seen that to produce a definite electromotive-force with a given number of conductors rotating at a given speed, a certain magnetic flux must be cut by them. The function of the field system of a dynamo is to provide this flux, which may be called the *useful flux* because it is the actual flux being cut by the conductors and producing

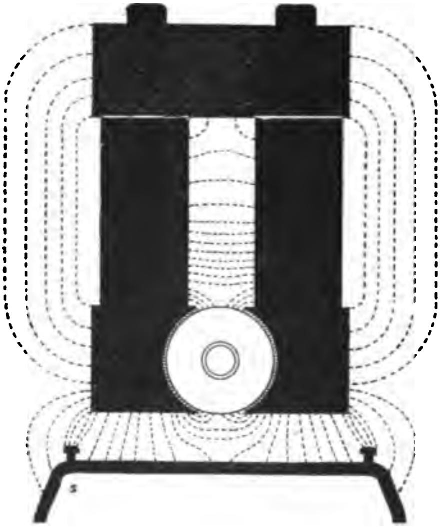


FIG. 72.—STRAY FIELD OF AN EDISON-HOPKINSON DYNAMO.

the electromotive-force. Now look at Fig. 72, which shows a typical bipolar magnetic circuit. In addition to the useful flux in the air-gap, there is a stray flux from all parts of the field system, and both the useful and stray fluxes have to be produced by the exciting ampere-turns wound on the magnet limbs.

If we call the total flux (per pole) produced by the exciting coils in the magnet core N_m, the useful flux which actually enters the armature N_a, and the stray flux which is dispersed N_s; then obviously

$$N_m = N_a + N_s.$$

The ratio of the stray flux to the useful flux is sometimes called the ***dispersion.*** The ratio of the total flux to the useful flux is called ***the coefficient of dispersion***, or ***coefficient of allowance for leakage***, or, less correctly, the ***leakage coefficient***, and is denoted by the symbol ν. Thus we have :—

$$\nu = \frac{N_m}{N_a}.$$

This coefficient of dispersion is therefore a number greater than unity. It varies between 1·15 and 1·7 in the usual types of machine.

Example.—In a certain 8-pole tramway generator the total flux per pole in the magnet core was 18,672,000 lines. Of these only 15,400,000 entered the armature, while 2,772,000 were dispersed. The coefficient of dispersion was therefore $\nu = 1 \cdot 18$, the stray flux being 18 per cent. of the useful flux.

Although the stray field does not directly cause a waste of energy, yet it is objectionable in any machine on account of the extra material that must be put into the field system to make up for it—that is, more iron is necessary in the yoke and pole cores to carry the extra flux, and the length of each turn of the copper winding round them is increased. It becomes of importance, therefore, to design magnetic circuits to have a minimum amount of magnetic dispersion in order to save cost. The magnitude of the stray field depends chiefly upon (*a*) shape of the magnet limbs—thus circular cores will have less leakage than those of rectangular shape, on account of the smaller area of the side flanks ; (*b*) upon the length of the air-gap, because the greater the reluctance of the latter the greater the tendency for the flux to take other alternative paths ; and (*c*) upon the degree of saturation to which the field system is pushed, because the magnetic conductivity of the leakage paths in the air is constant while that of the iron cores decreases as the degree of saturation is raised. It is evident, therefore also, that not only will the coefficient of dispersion vary with different types of machine, but it cannot, as a rule, be constant with a given machine but must vary with the excitation. Moreover, when a large current is being taken from the armature, the demagnetizing action of the armature due to the forward lead of the brushes, directly promotes dispersion, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines, tending to blow them aside, as it were.

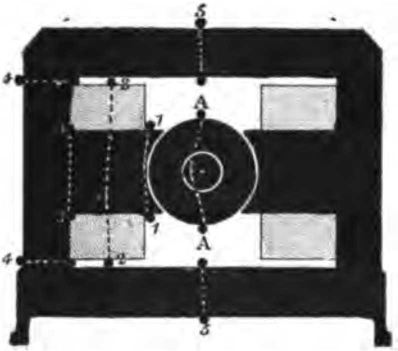


FIG. 73.—EXPLORING THE MAGNETIC DISPERSION OF A DYNAMO.

An idea of the actual distribution of the magnetic flux in the field system of a continuous-current machine, is given by the results of some measurements made by Lahmeyer upon the bipolar dynamo shown in Fig. 73. By means of a method presently to be described, he measured the flux across the armature at A and at the points I to V, along the magnetic circuit, his results being given in the table below.

A	780	100	1
I	788·5	101	1·01
II	861	110	1·10
III	876	112	1·12
IV	850	109	1·09
V	749	96	0·96

Column 2 gives the galvanometer readings for the exploring coils; and column 3 the percentage flux at each position in terms of the useful flux at A. The last column gives the coefficient of dispersion for the different distances along the magnet,

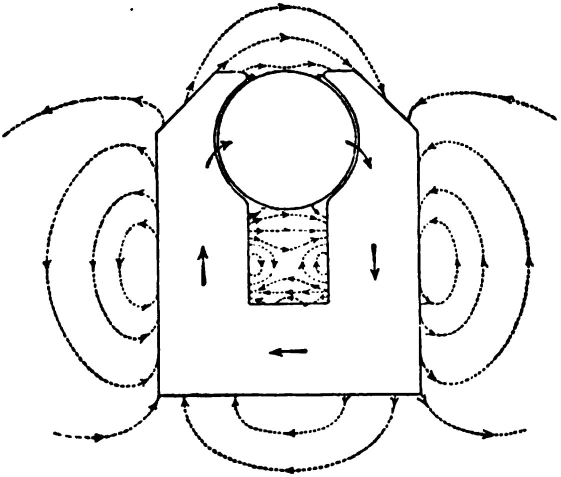


FIG. 74.—STRAY FIELD OF SIEMENS' DYNAMO.

the maximum being that at position III, and which value is therefore taken as the dispersion coefficient of the machine.

Fig. 74 shows the stray field of a Siemens and Halske bipolar machine of the "over" type, examined by Dr. Niethammer.

The most accurate way of finding the dispersion coefficient of a machine is by experiment. If in the case of a bipolar dynamo we wind around the armature a search coil with its plane at right angles to the magnetic flux, and connect it up to a ballistic galvanometer, we shall, upon making or breaking the exciting current, obtain a throw D_1 proportional to the flux passing from pole to pole. If the search coil be wound upon the limbs just at the neck of an exciting coil, a second throw D_2 may be obtained in the same way, and which will be proportional to the total flux produced by the windings. Then we have

$$\nu = \frac{D_2}{D_1}$$

for the particular excitation used.

Before each reading, the current in the fields should be reversed several times in order to wipe out any residual magnetism. In order to allow for the effect of the armature current, a few accumulators in series with an adjustable resistance may be connected to the brushes, and an appropriate lead given to them, the direction and amount of the current being such that the armature demagnetizes the field-magnets to the same extent as would be the case with the machine running on full load. The ratio of the maximum throw to the throw given by the armature search coil under these conditions will then approximately give the full-load dispersion coefficient. The principal objection to this method is the great strain it imposes upon the insulation of the magnet coils. As a general rule it cannot be employed with shunt windings, and for such machines a test-winding of fewer turns (and correspondingly larger section) must be wound on.

This method is due to the late Dr. J. Hopkinson, who found the dispersion coefficient of a bipolar dynamo of the "under" type to be 1·32.

Another method is by means of an alternate current. Wind on a search coil of S_2 turns as before, and connect it to a voltmeter. Now send an alternating current (preferably of low frequency) of known electromotive-force E_1 round the field coils, whose number of turns S_1 is known. Let the voltmeter reading be E_2. Then

$$N_M \propto \frac{E_1}{S_1} \text{ and } N_a \propto \frac{E_2}{S_2}.$$

Hence
$$\nu = \frac{E_1 \times S_2}{E_2 \times S_1}.$$

The eddy-currents produced by the alternating flux in the solid cores would not affect the results, but might be inconvenient if the current were left on too long.

The third way of determining the dispersion coefficient is by experiment upon the finished machine, whose dimensions and winding data are known. The method applied to a shunt machine is as follows.

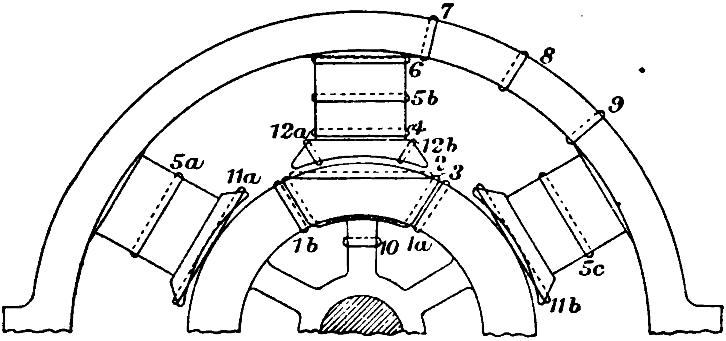


FIG. 75.—ESTIMATION OF DISPERSION BY EXPLORING-COILS.

Run the machine at its normal speed of n revolutions per second, with its full-load of C_a amperes. Measure the shunt current C_M, and electromotive-force at terminals V; and also note the lead of the brushes. From the resistance of the armature (brush to brush) and the load current, we calculate the ohmic drop as $R_a \times C_a$. This added to V gives E, the volts actually generated at full-load. The full-load useful flux must hence be

$$N_a = \frac{E \times 10^8}{n \times Z};$$

where Z stands for the number of armature conductors.

Now calculate (see page 152) the ampere-turns required to drive a flux of N_a lines through the whole magnetic circuit. Call them X_1. From the known lead of the brushes and the armature current calculate the value of the demagnetizing ampere-turns as indicated on page 258. Subtract them from the observed full-load ampere-turns $S_M C_M$, obtaining a value X_2. Then the dispersion coefficient is approximately given by

TABLE IX.—FLUXES IN VARIOUS PARTS OF A DYNAMO.

M P 6—400—500 (G. E. Co.).

Number of Coil Fig. 75.	Flux Through that Part		
	With 10·5 amperes in Field.	With 19·2 amperes in Field.	With 32·4 amperes in Field.
1*a*	2,220,000	2,670,000	3,060,000
1*b*	2,284,000	2,770,000	3,111,000
2	3,660,000	5,465,000	6,180,000
3	3,880,000	5,840,000	6,615,000
4	4,620,000	6,120,000	6,950,000
5*a*	4,895,000	6,350,000	7,400,000
5*b*	4,900,000	6,480,000	7,525,000
5*c*	4,750,000	6,290,000	7,333,000
6	4,830,000	6,470,000	7,385,000
7	2,356,000	3,120,000	3,575,000
8	2,480,000	3,100,000	3,470,000
9	2,500,000	3,120,000	3,500,000
10	34,000	44,200	54,000
11*a*	3,910 000	5,140,000	6,180,000
11*b*	4,000,000	5,200,000	6,115,000
12*a*	498,000	731,000	985,000
12*b*	473,000	728,000	934,000

$$\nu = \frac{X_2}{X_1}$$

To obtain a nearer approximation, take the value of demagnetizing ampere-turns as calculated, multiply by this value of ν, and then subtract from $S_M C_M$, obtaining a new value for X_2 to be used as above. But this method as a whole is not capable of giving very accurate results.

A highly detailed examination was made at Schenectady upon a multipolar dynamo, to ascertain the fluxes through the various parts. A large number of exploring coils were wound over the machine as indicated in the accompanying Fig. 75. The results are given in Table IX.

Looking at the figures in the last column, with the excitation at its highest, we see that the maximum flux in the pole-core was about 7,400,000 lines. Of these about 6,180,000 actually entered the armature, the sum of the fluxes measured by exploring coils Nos. 1*a* and 1*b* agreeing closely with that of No. 2. The yoke appears to be of insufficient section, as the flux passing through No. 8 is less than half of that through Nos. 5 or 6. Taking the figures above we see that the coefficient of dispersion at the highest excitation is $\nu = 1 \cdot 19$.

TABLE X.—DISPERSION COEFFICIENTS.

Output in Kilowatts	Over-type as No. 23, p. 119.	Under-type as No. 2, p. 116.	Single-Magnet Type, as No. 31, p. 120.	Man-chester Type, as No. 24, p. 119.	Bi-polar Iron-clad Type, as No. 25. p. 119.	Double Horse-shoe Type, as No. 6, p. 116.	Four-pole Iron-clad Type, as No. 22, p. 116.	Multi-polar Type, as No. 28, p. 119.
1 to 5	1·4	1·6	1·55	1·7	1·30	1·65	1·75	1·5
5 to 25	1·28	1·45	1·4	1·55	1·22	1·5	1·55	1·32
25 to 100	1·22	1·35	1·32	1·45	1·16	1·4	1·45	1·28
100 to 300	..	1·25	..	..	..	..	1·27	1·22
300 to 1000	..	..	..	..	..	..	..	1·12

Table X. given above shows the value of the dispersion coefficient for various types and sizes of machines, the values in every case being if anything in excess of the true amount, as they have been obtained from calculation and experiment under the most unfavourable conditions.[1] Magnetic dispersion is always greater with the smaller sizes of machine, on account of the difficulty of properly dimensioning the field-system. It is also greater with cast-iron magnets and pole-pieces, and as we have seen already, with smooth core armatures. The values given below may consequently be looked upon as being high for slotted armatures and wrought-iron or cast-steel fields.

CALCULATION OF DISPERSION.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of dispersion. Calculations of the dispersion are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry[2] on this point. It follows that along any branched part the joint *permeance*[3] (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of dispersion, ν, can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux u and the waste flux w; then

---

[1] See *Dynamo-machines*, by A. Wiener, 1902. For earlier data on the stray fields of dynamos, see Hering in *El. Rev.*, xxi. 186 and 205, 1887: Carhart, *Electrician*, xxiii. 644, 1889; Wedding, *Electrot. Zeitschrift*, xiii. 67, 1892; Mavor, *Electrical Engineer*, xii. 428, 1894: W. B. Esson in *Journ. Inst. Electrical Engineers*, Feb. 1890; and W. L. Puffer in *Technology Quarterly*, iv. 205, Oct. 1891. Some recent researches on magnetic dispersion are those of Rothert in the *Elektrotechnische Zeitschrift* for May 26, 1898; and Picou, *Bulletin Soc. Internat. des Électriciens*, June 1902, p. 425. Attempts to reduce dispersion are discussed by Kelly in *Electrical World*, xxxii. 161, 1898, and by Guilbert in *L'Éclairage Électrique*, xviii. 298, 1899.

[2] *Journ. Soc. Teleg. Engineers and Electricians*, 530, 1886.

[3] *Permeance* is of course the reciprocal of magnetic reluctance; just as electric conductance is the reciprocal of electric resistance.

$$\nu = \frac{u + w}{u}.$$

But each of these is a complicated quantity; therefore the more complete formula is

$$\nu = \frac{u_1 + u_2 + u_3 + \ldots\ldots + w_1 + w_2 + w_3 + \ldots\ldots}{u_1 + u_2 + u_3 + \ldots\ldots}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or lemmas originally suggested by Professor Forbes,[1] which consist in certain approximate integrations. For the convenience of British engineers the values have been re-calculated into inch measures instead of centimetre measures.

The unit reluctance and unit permeance are so chosen as to obviate the subsequent necessity of multiplying the ampere-turns by $4\pi \div 10$. This will make the reluctance of the inch cube of air equal to $10 \div 4\pi$ divided by $2 \cdot 54 = 0 \cdot 3133$; and its permeance to $3 \cdot 1918$.[2]

Rule I.—Permeance between two parallel areas facing one another. Assume (Fig. 76) that the magnetic lines are straight and equally distributed over the surface: then,

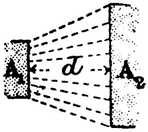


FIG. 76.

Permeance = $3 \cdot 1918 \times$ mean area (square inches) $\div$ distance (inches) between them

$$= 1 \cdot 596 \times (A_1'' + A_2'') \div d''.$$

Rule II.—Permeance between two equal adjacent rectangular areas lying in one plane. Assuming the lines of flux to be semicircles, and that distances d_1'' and d_2'' between their nearest and furthest edges respectively are given ; also a'' their width along the parallel edge :—

---

[1] *Journ. Soc. Teleg. Engineers*, xv. 551, 1886.

[2] See the Author's work *The Electromagnet.*

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10} \frac{d_2''}{d_1''}.$$

Rule III.—Permeance between two equal parallel rectangular areas lying in one plane at some distance apart. Assume (Fig. 78) the lines of flux to be quadrants joined by straight lines :—

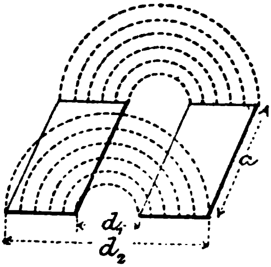


FIG. 77.

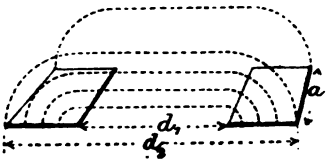


FIG. 78.

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10}\left\{1 + \frac{\pi(d_2'' - d_1'')}{d_1''}\right\}.$$

Rule IV.—Permeance between two equal areas at right-angles to one another.

Permeance = double the respective values calculated by Rule II.

If measures are given in centimetres these rules become the following :—

I. $\frac{1}{2}(A_1 + A_2) \div d.$

II. $\frac{a}{\pi}$ hyp. log $\frac{d_2}{d_1}.$

III. $\frac{a}{\pi}$ hyp. log $\left(1 + \frac{\pi(d_2 - d_1)}{d_1}\right).$

Using these rules to predetermine the stray field to fly-wheels, pedestals and shafts, it is possible from the working drawings to predict the performance of a machine to within 2 per cent.

The author has given (in his work on *The Electromagnet*) some further rules, including the case of permeance between two parallel cylindrical limbs. The reader should also consult the writings of Kapp,[1] Wiener[2] and Arnold[3] for the predetermination of the dispersion coefficient, the last named author going into the question at great length.

Goldsborough[4] has laid down the theorem that, assuming a fixed difference of magnetic potential between the surface of a pole-piece and that of an armature core (the latter surface supposed to be smooth), *the intensity of the magnetic field at any point at the surface of the armature will be proportional to the sum of the reciprocals of the distances of that point from all the points on the perimeter of the pole-piece made by a section-plane passing through that point.* On this principle he has calculated the distribution of the flux in the gaps in certain cases.

By definition the dispersion coefficient $\nu = (N_a + N_s) \div N_a$; and as the useful and stray fluxes are respectively proportional to the permeances of the useful and stray paths, if we write P_u for the permeance through the gap and teeth, and P_s for the permeance of the stray field, we may write $\nu = (P_u + P_s) \div P_u$. Now P_s is a constant, being through air, whereas P_u being partly through air and partly through iron will diminish as the saturation of the teeth increases towards full-load. Hence ν will rise as the excitation is increased.

DETERMINATION OF EXCITING AMPERE-TURNS.

The calculation of the ampere-turns necessary to drive a certain useful flux N_a across the air-gap of a dynamo is a straightforward matter if we know the dispersion coefficient of the machine, and the magnetic properties of the materials used to carry the flux, as laid down in curves such as those in Plate I.

---

[1] *Elektromechanische Konstructionen*, by G. Kapp, p. 9.

[2] *Dynamo-machines*, by A. Wiener, 1902, pp. 217-265, and 614-628.

[3] *Die Gleichstrom-Maschinen*, 1902; see also *Electrical Engineer*, Sept. 11 1903, p. 395.

[4] *Trans. Amer. Inst. El. Engineers*, June 30, 1898, p. 515.

The method of using these curves for the purposes of dynamo calculation is as follows. We are given—

N_a useful flux per pole;
A_1 magnetic area of yoke;
A_2 „ of field-cores;
A_3 „ of air-gap;
A_4 „ of teeth under one pole;
A_5 „ of armature core;
L_1 length of magnetic path in yoke;
L_2 „ „ in two field-cores;
L_3 „ „ in two air-gaps;
L_4 „ „ in two teeth;
L_5 „ „ through armature core;

and the question is to find the ampere-turns per pair of poles necessary to produce the flux of N_a magnetic lines in the air-gap.

Now the total flux is

$$N_m = \nu N_a.$$

Consequently, by dividing this by the magnetic area of yoke and magnet-cores we obtain

B_1 flux-density in the yoke.
B_2 „ in the magnet-cores.

Also, by dividing the useful flux N_a by the magnetic area of air-gap, teeth and armature-core, we obtain respectively

B_3 flux-density in air-gap.
B_4 „ in teeth.
B_5 „ in armature-core.

To find the ampere-turns necessary for yoke, magnet-cores, teeth, and armature-core, all we have to do is to take the magnetizing curve for the respective material, and see how many ampere-turns per unit length are required when these parts are worked at flux-densities of B_1, B_2, B_4 and B_5, respectively. Let the numbers so found be noted by δ_1, δ_2, δ_4 and δ_5. Then

Ampere-turns for yoke $= L_1 \times \delta_1$
" for two field-cores $= L_2 \times \delta_2$
" for two sets of teeth $= L_4 \times \delta_4$
" for armature-core $= L_5 \times \delta_5$

With regard to the ampere-turns for the air-gaps, we have to resort to the use of *gap-coefficients.* The coefficient is $10 \div 4\pi$ if centimetre units are used; or if the flux-density is in lines per square inch, and the length of magnetic path is reckoned in inches, the coefficient becomes 0·3133. These coefficients are used as follows:—

Ampere-turns for gaps $= 0\cdot8 \times \mathfrak{B}'_3 \times L'_3$ in centimetre units.
" " $= 0\cdot3133 \times B_3 \times L_3$ in inch units.

The sum of the ampere-turns required for the different parts will then give us the total ampere-turns required per pair of poles.

Some little discretion must be used in reckoning out what may be termed the "magnetic dimensions" of the machine, that is, *the mean magnetic path*, and the *effective iron area* traversed by the flux. It may not be out of place to take up this question a little more fully.

(*a*) *Yoke.*—The only point to be remembered here is that in multipolar machines the yokes will only carry half the total flux, as it will divide each way. The magnetic length is the mean length of path.

(*b*) *Magnet-Cores.*—The magnetic section is simply the section of one core. The magnetic length L_2 is that of two pole-cores.

(*c*) *Air-gap.*—The length is twice the distance from iron to iron. With regard to the magnetic section to be taken, it is always more or less a matter of judgment and experience, on account of the spreading of the flux from the pole-piece, or *fringing* as it is frequently called. For machines having smooth core armatures, and where the length of pole-piece is equal to the gross length of the armature core, the magnetic area of the air-gap may be taken as the area of one pole-piece *plus* a small area equal to the length of one air-gap multiplied by the periphery of one pole-piece. For machines with slotted armatures, the air-gap area may be taken as the mean of the pole-face area and of the *iron* area at the face of the teeth under one pole. But the number of teeth so reckoned should be increased by one or two over the actual number under one pole, to allow for the fringing; such allowance depending upon the length of the gap, shape of the teeth at the armature periphery, and flux-density at which they are worked. On account of distortion of the field, the magnetic area of the air-gap may be different at full-load from what it is at no-load, but the two rules above will generally be found good enough.

(*d*) *Armature Core.*—Here again if the machine is multipolar, the core will only have to carry half the useful flux. The magnetic length is the length of the mean path lying between the roots of the teeth and the periphery of the internal hole. The magnetic section is less than the gross section by 10 to 25 per cent., on account of the insulation of the core-disks and the presence of ventilating ducts. If these latter are absent, as is usually the case with small armatures, allow 10 per cent. as space-loss if the disks are varnished, and 15 per cent. if paper insulation is employed. If air-ducts are present, their width must be subtracted from the gross length when computing the area. For paper-insulated armatures with the usual allowance of ventilating ducts, the net length of core (parallel to shaft) is generally from 65 to 75 per cent. of the gross length.

(*e*) *Teeth.*—The total length of tooth traversed by the flux is equal to the depth of a slot multiplied by 2. The width of one tooth to be taken as the mean width. The number lying under one pole may be taken as the number of teeth in the polar angle plus one or two, depending on the length of the air-gap, in order to allow for spreading. The magnetic area of one tooth will therefore be the mean width of tooth multiplied by the net length of armature (that is, gross length *minus* total width of air-ducts *minus* 10 to 15 per cent. space lost through insulation). But there is yet an important point. If the teeth are worked at densities of 100,000 lines, or more, per square inch, part of the useful flux will pass into the core by way of the slots, because these offer a path in parallel whose magnetic conductivity is comparable with that of the teeth themselves.

It follows, therefore, that the ampere-turns for the teeth calculated out on the basis that they carry the whole of the flux, will be in excess of the right amount at high values of tooth flux-density. We will now proceed to show how the true value of tooth flux-density B_4 may be estimated if we know the apparent flux-density in the teeth which we will call B_a. Further, we will denote by

b_1 mean width of tooth;
b_2 width of slot;
l net length of armature, that is, the *iron* length parallel to shaft;
h height or depth of slot;
f ratio of net length to gross length of armature core;
N_a flux from one pole, as before;
N_4 flux actually carried by teeth.

Then we have

$$\text{Iron section of one tooth} = b_1 \times l.$$

$$\text{Air } \;,, \;\; ,, \;\; ,, \;\text{ slot} = \frac{b_2 \times l}{f}.$$

The actual section of air-space per slot forming an alternative path in parallel for the flux is given by the area of one slot *plus* the area of the space lost along one *tooth* by insulation and ventilating ducts, or

$$\left.\begin{array}{c}\text{Section of air-space}\\ \text{per slot}\end{array}\right\} = \frac{b_2 \times l}{f} + (1 - f)\frac{b_1 \times l}{f}$$

$$= \frac{l(b_1 + b_2 - b_1 f)}{f}.$$

Now the flux N_a coming out of the pole-piece will divide itself between tooth and air-space in inverse proportion to the reluctance of these two. The flux in the air-space is $(N_a - N_4)$.

Hence we have

$$N_4 \propto \frac{b_1 \times l \times \mu}{h},$$

where μ is the permeability of the tooth when transmitting the actual flux N_4.

Also $$(N_a - N_4) \propto \frac{l(b_1 + b_2 - b_1 f)}{f \times h}$$

and by division

$$\frac{N_4}{(N_a - N_4)} = \frac{f b_1 \mu}{b_1 + b_2 - b_1 f}$$

$$N_4 (b_1 + b_2 - b_1 f + b_1 f \mu) = N_a f b_1 \mu.$$

$$\frac{N_4}{N_a} = \frac{f b_1 \mu}{b_1 + b_2 - b_1 f + b_1 f \mu} = \frac{B_4}{B_a}.$$

As stated above, a common ratio of iron length to gross length for slotted armatures with air-ducts and paper insulation is 0·75. Putting in this value of f in the above equation we have

$$\frac{B_4}{B_a} = \frac{0{\cdot}75 \times b_1 \mu}{b_2 + 0{\cdot}25\, b_1 + 0{\cdot}75\, b_1 \mu}$$

or $$\frac{B_4}{B_a} = \frac{b_1 \mu}{1{\cdot}34\, b_2 + 0{\cdot}33\, b_1 + b_1 \mu}.$$

To put this into practical shape, take the ratio of b_1 to b_2, assume values for B_4, find the corresponding permeabilities from such a curve as that of Fig. 51, and calculate B_a. Then a curve connecting B_a and B_4 for this particular ratio of b_1 to b_2 can be plotted, showing what the *true flux-density* in the teeth is when the *apparent flux-density* (that is, total flux per pole divided by iron area of teeth under one pole, or $N_a \div A_4 = B_a$) has any particular value. This has been done in the three curves shown in Fig. 79 for three usual ratios of b_1 to b_2 using the above equation. If f has a value different from 0·75, the equation should be correspondingly altered and new curves plotted when great accuracy is desired.

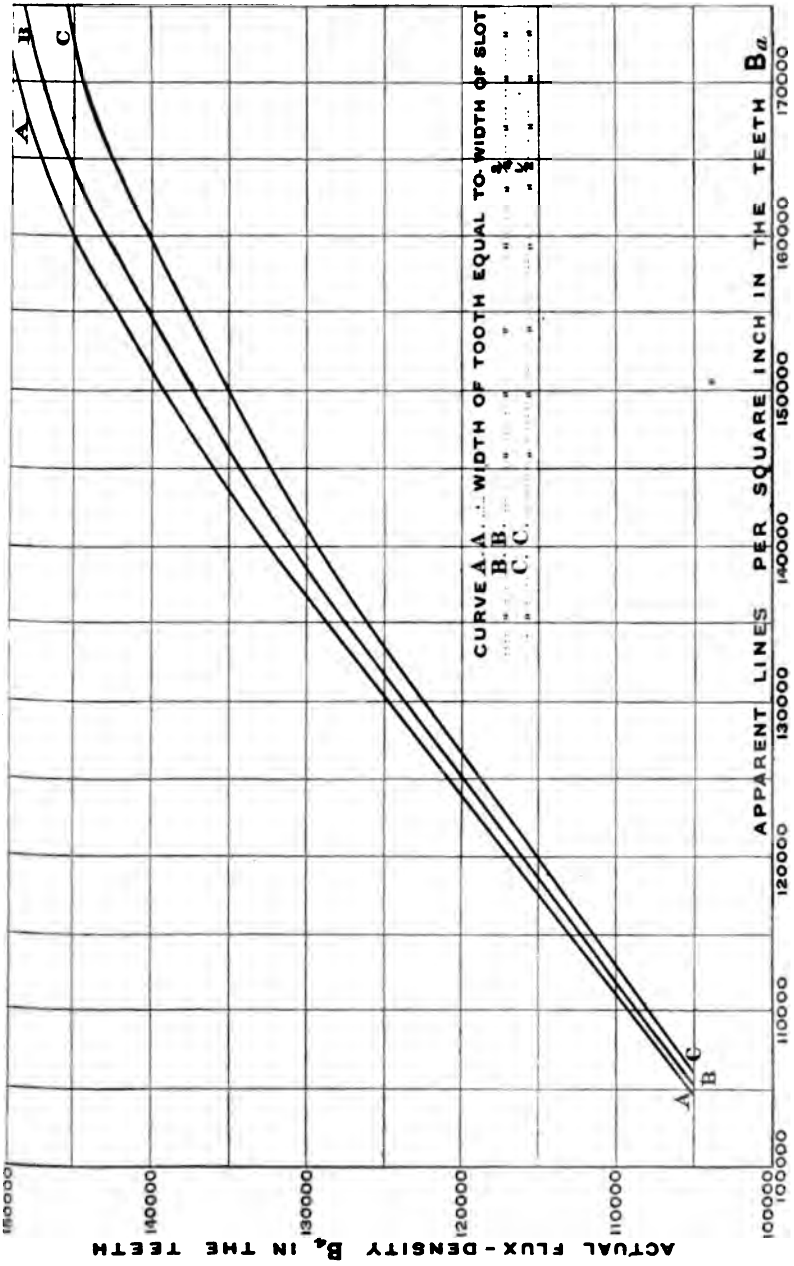


FIG. 79.—APPARENT AND ACTUAL FLUX-DENSITIES IN TEETH.

EXAMPLE OF CALCULATION.

In order that the foregoing rules may be clearly understood, and to exemplify the use of the curves, etc., we will take a concrete case for purpose of illustration. In Fig. 80 is given a dimensioned sketch of part of a modern six-pole 200 kilowatt machine. We will proceed to calculate how many ampere-turns per pair of poles are required in order to produce a flux of 12,500,000 lines through the air-gap.

A reference to the table of dispersion coefficients on page 137 gives us an approximate figure,

$$\nu = 1 \cdot 18,$$

and hence,

$$N_m = N_a \times 1 \cdot 18 = 14{,}750{,}000.$$

The next thing to do is to make an estimate of the magnetic lengths and areas. We have

Yoke.— Area $= 17 \cdot 5 \times 5$

$$A_1 = 87 \cdot 5 \text{ square inches.}$$

For the length of mean path, we can either scale it off from the drawing, which is, as a rule, more convenient, or estimate it from

$$L_1 = 5 + \left\{ \frac{(59 \cdot 9 + 33 \cdot 5 + 5) \times 3 \cdot 14}{6} \right\}$$

$$= 56 \cdot 5 \text{ inches.}$$

As no allowance has here been made for the rounding off of corners along the mean path taken by the flux, we may say

$$L_1 = 55.$$

Magnet Cores.—As these are circular, we have

$$A_2 = 14 \cdot 25 \times 14 \cdot 25 \times 0 \cdot 785$$
$$= 159 \cdot 5 \text{ square inches.}$$

The magnetic length of the two cores and pole-pieces is

$$L_2 = 2 \times 16 \cdot 75 = 33 \cdot 5.$$

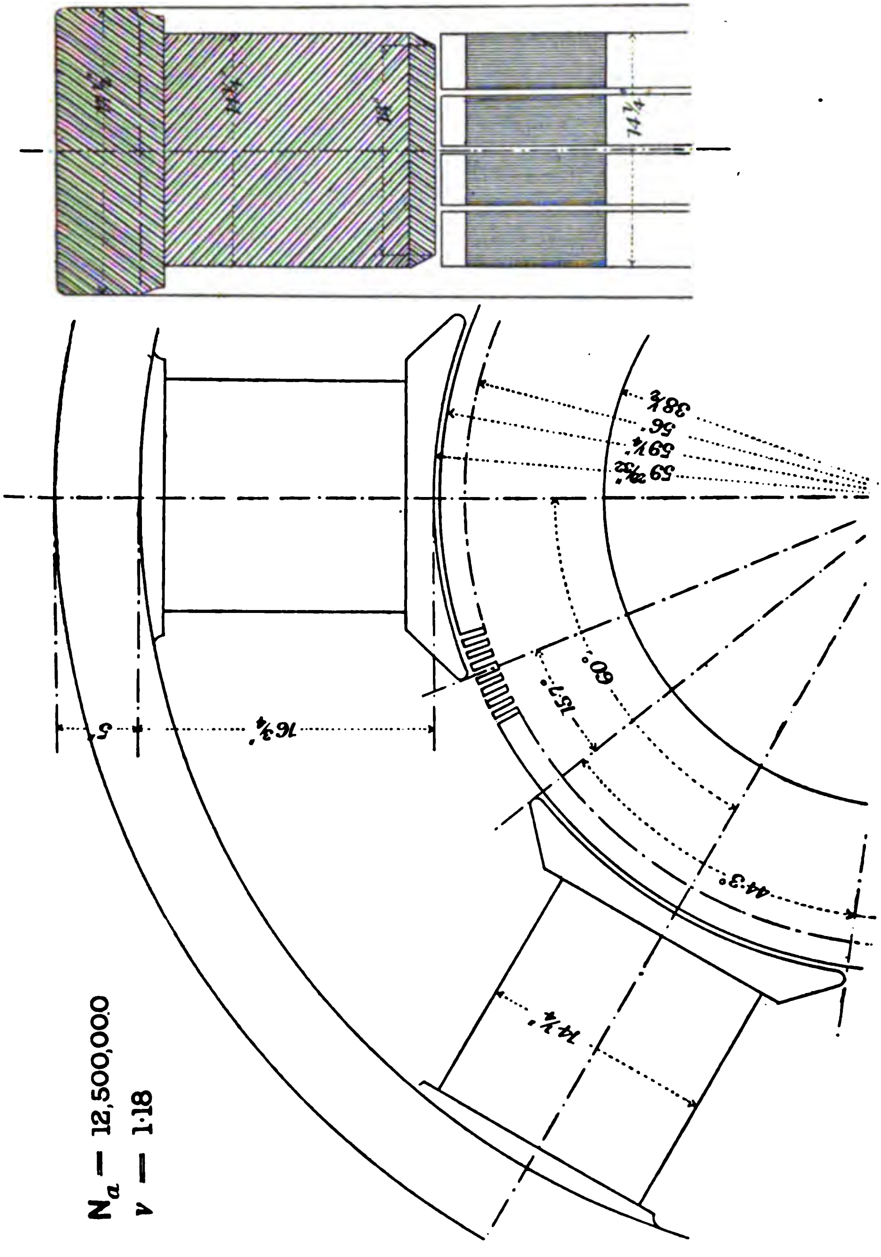


FIG. 80.—MAGNETIC CIRCUIT FOR CALCULATION. (MP 6-200-180-500V-400A.)

Air-gaps.—

$$L_3 = 59{\cdot}9 - 59{\cdot}25$$
$$= 0{\cdot}65 \text{ inch.}$$

For the area, we take, as stated above, the mean between pole-piece area and the area of the teeth under one pole at their tops. As the air-space in this machine is short, we take for the number of teeth acted on by one pole the actual number lying in the polar angle, *plus one*. Had the air-space been longer we should have added *two*.[1]

From the sketch we see that the polar angle is 44·3°. As there are altogether 220 teeth, the number in the actual polar angle is

$$220 \times \frac{44{\cdot}3}{360} = 27.$$

Adding one to this, we have 28 as the number transmitting the flux. Now the iron area of a single tooth at the top is

$$\left\{14{\cdot}25 - (3 \times 0{\cdot}375)\right\} \times 0{\cdot}9 \times 0{\cdot}429$$
$$= 5{\cdot}06 \text{ square inches;}$$

where 0·9 is the ratio of the net iron length to the gross length of the iron core from front to back and 0·429 is the width of the tooth at the top.

The iron area at the top of the teeth under one pole is hence

$$28 \times 5{\cdot}06 = 142 \text{ square inches.}$$

And the area of the pole-face is

$$13 \times \left(59{\cdot}9 \times 3{\cdot}1416 \times \frac{44{\cdot}3}{360}\right)$$
$$= 302 \text{ square inches.}$$

---

[1] This allowance for the *fringing* of the magnetic field, which increases the useful flux entering the armature from one pole, is a matter of judgment and experience. Fischer-Hinnen has given elaborate rules. For smooth-cored armatures it is usual to estimate the width of the fringe as equal to the gap from iron to iron. See a paper also by Sander in the *Zeitschrift für Elektrotechnik*, xviii. 562. Nov. 1900.

Hence, we have for the magnetic area of the air-space,

$$A_3 = \frac{142 + 302}{2} = 222 \text{ square inches.}$$

Teeth.—For the magnetic length we have

$$L_4 = 2 \times 1 \cdot 625 = 3 \cdot 25 \text{ inches};$$

where 1·625 is the length of the tooth. The mean iron area of the 28 teeth acted upon by one pole, if the mean width of a tooth is 0·406, is

$$\{14 \cdot 25 - (3 \times 0 \cdot 375)\} \times 0 \cdot 9 \times 0 \cdot 406 \times 28,$$

$$A_4 = 134 \cdot 5 \text{ square inches.}$$

Armature Core.—The mean length of the path taken by the flux is best obtained from the drawing; otherwise we have

$$8 \cdot 75 + \left\{ \left(\frac{56 + 38 \cdot 5}{2} \right) \times 3 \cdot 14 \times \frac{1}{6} \right\}'$$

$$= 33 \cdot 55 \text{ inches.}$$

Or say $L_5 = 33$ inches.

The magnetic area is

$$\{14 \cdot 25 - (3 \times 0 \cdot 375)\} \times 0 \cdot 9 \times 8 \cdot 75,$$
$$A_5 = 103 \cdot 5 \text{ square inches.}$$

Having now found the magnetic dimensions, we can construct the table given on next page. The flux-densities have been obtained by dividing the flux in each part by the corresponding magnetic area; as the density in the teeth is in this case below 100,000, we may assume that no correction is necessary—that is, we may consider $B_a = B_4$, the entire flux being carried by the teeth. The rest of the working is sufficiently obvious, the final result being that to force the 12·5 megalines through the iron and across the gaps, something over 14,000 ampere-turns per pair of poles are required. The actual number would be taken in practice as 15,000 at least, in order to allow for differences in the iron, etc.

By similar calculations we can find the ampere-turns required to force other values of N_a across the air-gap and through the iron parts of the machine. By plotting the values of excitation so obtained against the corresponding values of N_a, we obtain what is known as the ***saturation curve*** of the magnetic circuit in question; the ordinates of the curve representing also the corresponding values of the induced electromotive-force to a different scale. Examples of such calculated curves will be found in Chapter XIX. on Examples of Dynamo Design.

$N_a = 12{,}500{,}000$; $N_m = 14{,}750{,}000$; $\nu = 1 \cdot 18$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-Density.	Value of δ from Curves.	Ampere-turns Required.
Yoke	Cast steel	55	87·5	84100	24·2	1330
2 Magnet-cores	Ditto	33·5	159·5	92500	32·5	1090
2 Air-gaps	Air	0·65	222	56300	×0·3133*	11500
2 Teeth	Sheet iron	3·25	134·5	93000	19	62
Armature-core	Ditto	33	103·5	60400	4	132

Total ampere-turns per pair of poles = 14114.

We have here calculated the ampere-turns needed for a *pair of poles*; but as the two halves of the magnetic circuit so considered are alike, one may, if preferred, calculate simply the ampere-turns *per pole*, taking only one-half of a magnetic circuit, including, of course, one gap, one pole-core, etc., and

---

* This number 0·3133 is the *gap-coefficient* and represents the number of ampere-turns per inch length of path requisite for a flux-density of 1 line per square inch. Multiplying the flux-density of the preceding column by this coefficient gives the number of ampere-turns needed for that density, per inch of path in air; and multiplying this number by the magnetic length of the 2 air-gaps, in column 3, gives finally the number of ampere-turns needed for the 2 gaps:

$$56300 \times 0 \cdot 3133 \times 0 \cdot 65 = 11500.$$

taking yoke and armature core at half the lengths estimated as above. A convenient form of schedule for such calculations will be found in the Appendix to Chapter XVIII., p. 580.

In a careful study, in part theoretical, but confirmed by experiments, Goldsborough[1] has shown that in the armature of a multipolar dynamo the paths of the magnetic lines through the armature core are not symmetrical, and that they are not distributed with equal density through the cross-section of the core (Fig. 81), being denser in the region immediately below the roots of the teeth, and less dense near the internal circumference of the core. At full-load these inequalities are more marked. As a consequence any calculations as to hysteretic losses in the core made on the assumption of uniform distribution will understate the actual waste of energy.

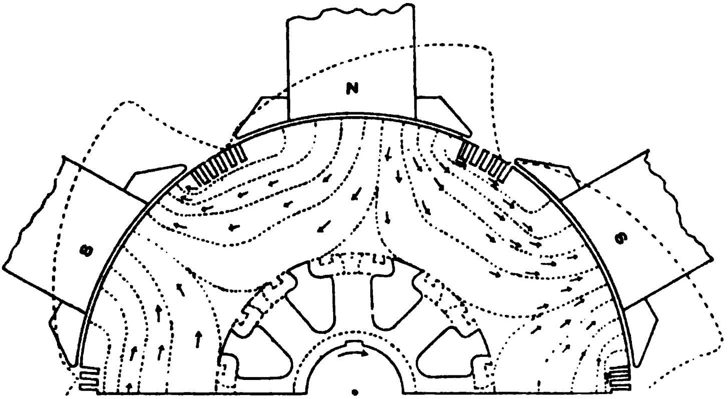


FIG. 81.—CORE-DISTRIBUTION OF FLUX.

Similarly, Herr Dettmar has shown in the *Elektrotechnische Zeitschrift* for 1900, vol. xxi. 944, that the density of the flux in the core-body diminishes, not quite in arithmetical proportion, from a maximum below the roots of the teeth to a minimum at the internal periphery.

If the pole-pieces are not laminated, the width of the gap should not be much less than about 1½ times the width of the slot, otherwise the unequal distribution of the flux at the pole-face will set up harmful eddy-currents.

---

[1] Air-gap and Core Distribution Studies, *Trans. Amer. Inst. El. Engineers*, June 1899, p. 461.

Professors H. Hele-Shaw and A. Hay have published in the *Philosophical Transactions*, cxcv. 303, 1900, a very remarkable paper on lines of induction in a magnetic field, the distribution of which they have studied by the aid of a beautiful hydraulic model in which the stream-lines in glycerine imitate the forms of the magnetic lines under varying conditions. Amongst these they show the distribution in the case of a toothed armature with a gap approximately equal to the breadth of a tooth and with slot slightly wider. In the gap the density of the lines shows alternate maxima and minima, the lines being very slightly curved at the level of the teeth; but below this level those that enter the slot swerve sharply round (Fig. 82) to enter the flanks of the teeth.

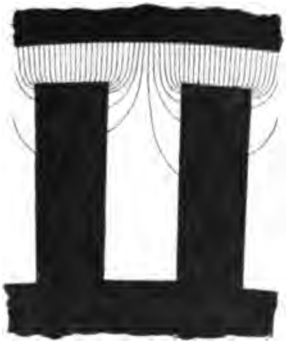


FIG. 82.

Except in the case of very highly saturated teeth, there is no field in the slot at any greater depth than about equal to the slot width. The ratio of the density of the field in the slot to the density of field in the tooth is roughly the same as the ratio of the gap-length (from iron to iron) to the sum of gap-length and tooth-length.

Herr Dick has shown, in the *Electrotechnische Zeitschrift* for July 1901, that if account is taken of the flux-densities along the tooth, the ampere-turns actually needed will be considerably less than the number (only about $\frac{2}{3}$) calculated from the mean between the maximum value at the roots and the minimum value at the tops of the teeth. In the same journal for November 1901, Dr. Corsepius has shown how the design of armatures is dependent on the ratio between the width of the tooth and the width of the slot.

CHAPTER VII.

COPPER CALCULATIONS: COIL WINDINGS.

Weight of Copper Wire.—Pure copper has a specific gravity of 8·9 at the ordinary atmospheric temperature of 15° C. Hence—

1 cubic centimetre	weighs	8·9 grammes;
1 cubic foot	„	555 pounds;
1 cubic inch	„	0·3213 pounds.

A rod of copper 1 inch in diameter, and 1 foot in length weighs 3·028 lb. Hence the weight of a copper wire can be found by multiplying together its length in feet, its sectional area in square inches, and the coefficient 3·028. A wire 1 mil in diameter and 1 foot long weighs 0·000003028 lb. Hence if d be the diameter *in mils*, and l the length *in feet*, the weight of the wire will be—

$$\text{weight in lb.} = d^2 \times l \times 0{\cdot}000003028;$$

or a wire d mils in diameter weighs $\frac{d^2}{330250}$ lb. per foot.

Example.—30 feet of a No. 1 S.W.G. copper wire, which is 300 mils in diameter, weighs 8·17 lb.

In the case of copper strip of rectangular section, if the width and depth of the strip are given in mils, and the length in feet, the weight in pounds can be found from the rule that weight in lb. = sectional area in sq. mils × l × 0·000003855.

Electric Resistance of Copper.—Pure copper has a specific resistance that increases slightly with temperature.

The resistance of a centimetre cube of pure copper, in ohms, has the following values:—

	At 0° C.	At 15° C.	At 30° C.	At 60° C.
Annealed	0·00000159039	0·00000169259	0·00000179559	0·00000200401
Hard-drawn	0·00000162246	0·00000172676	0·00000183180	0·00000204442

	At 32° F.	At 60° F.	At 115° F.
Annealed	0·00000159039	0·00000169639	0·00000190711
Hard-drawn	0·00000162246	0·00000173054	0·00000194557

The rise of resistance of copper with temperature is approximately $\frac{4}{10}$ of one per cent. per Centigrade degree, or $\frac{2}{9}$ of one per cent. per Fahrenheit degree.

If the resistance $R_{0^\circ C.}$ at freezing-point, of any copper conductor be known, its resistance $R_{\theta^\circ C.}$ at any temperature θ on the Centigrade scale, can be accurately calculated by the formula of Clarke, Forde and Taylor:

$$R_{\theta^\circ C.} = R_{0^\circ C.} \{1 + 0{\cdot}00426744\,\theta + 0{\cdot}0000011193\,\theta^2\};$$

or on the Fahrenheit scale,

$$R_{\theta^\circ F.} = R_{32^\circ F.} \{1 + 0{\cdot}0023708(\theta - 32) + 0{\cdot}00000034548(\theta - 32)^2\}.$$

The following are some useful rules for calculating the resistances of copper as used in the construction of electric machines. In all cases it is assumed that the material is pure annealed copper, commonly called "high conductivity" copper. If the copper is "hard drawn" instead of "annealed" the resistance may be some 2 per cent. greater for an equal cross-section and equal length. Resistances are given in ohms.

British Units.—Resistance of 1 inch cube is

0·00000062615	at	0° C. or 32° F.
0·00000066639	at	15° C.
0·00000066788	at	60° F.
0·00000070694	at	30° C.
0·00000075085	at	115° F.
0·00000078899	at	60° C.

A rod of copper, 1 foot long and 1 square inch in cross-section, has the following resistance:—

0·0000075138 at 0° C.
0·0000079966 at 15° C.
0·0000084833 at 30° C.
0·0000094679 at 60° C.

A rod of round copper, 1 foot long and 1 inch in diameter (having therefore a sectional area of 1 circular inch), has the following resistance:—

0·0000095664 at 0° C.
0·0000101812 at 15° C.
0·0000108007 at 30° C.
0·0000120545 at 60° C.

A wire of copper, 1 foot long and having a sectional area of 1 square mil, has the following resistance:—

7·5138 ohms at 0° C.
7·9966 „ at 15° C.
8·4833 „ at 30° C.
9·4679 „ at 60° C.

A round wire of copper, 1 foot long, having a diameter of 1 mil (and therefore having a sectional area of 1 circular mil), has the following resistance:—

9·5664 ohms at 0° C.
10·1812 „ at 15° C.
10·8007 „ at 30° C.
12·0545 „ at 60° C.

The resistance of a *copper strip*, the length of which is given in feet and the sectional area in square mils, may therefore be calculated by the rule:—

$$\left.\begin{array}{lll}\text{At } 0^\circ\text{ C. ohms per foot} & = & 7{\cdot}5138\\ \text{At } 15^\circ\text{ C.}\qquad ,, & = & 7{\cdot}9966\\ \text{At } 30^\circ\text{ C.}\qquad ,, & = & 8{\cdot}4833\\ \text{At } 60^\circ\text{ C.}\qquad ,, & = & 9{\cdot}4679\end{array}\right\}\begin{array}{c}\text{divided by}\\ \text{area in}\\ \text{sq. mils.}\end{array}$$

The resistance of a *round copper wire*, the length of which is given in feet and the diameter in mils (which diameter, if squared, gives the sectional area in circular mils) may therefore be calculated by the rule :—

$$\left.\begin{array}{llll} \text{At } 0^\circ \text{ C. ohms per foot} & = & 9{\cdot}5664 \\ \text{At } 15^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 10{\cdot}1812 \\ \text{At } 30^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 10{\cdot}8007 \\ \text{At } 60^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 12{\cdot}0545 \end{array}\right\} \begin{array}{c}\text{divided by} \\ \text{diameter} \\ \text{squared.}\end{array}$$

Metric Units.—A rod of copper, 1 metre long and of 1 square millimetre cross section, has the following resistance :—

0·0159039	ohm	at	0° C.
0·0169259	„	at	15° C.
0·0179559	„	at	30° C.
0·0200401	„	at	60° C.

A round wire of copper, 1 metre long and 1 millimetre in diameter, has the following resistance :—

0·0202487	ohm	at	0° C.
0·0215499	„	at	15° C.
0·0228614	„	at	30° C.
0·0255148	„	at	60° C.

The resistance of a *copper strip*, the length of which is given in metres and the sectional area in square millimetres, may therefore be calculated by the rule :—

$$\left.\begin{array}{llll} \text{At } 0^\circ \text{ C. ohms per metre} & = & 0{\cdot}0159039 \\ \text{At } 15^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0169259 \\ \text{At } 30^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0179559 \\ \text{At } 60^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0200401 \end{array}\right\} \begin{array}{c}\text{divided by} \\ \text{sq. milli-} \\ \text{metres.}\end{array}$$

The resistance of a *round wire* the length of which is given in metres and the diameter in millimetres, may be calculated by the rule :—

$$\left.\begin{array}{llll} \text{At } 0^\circ \text{ C. ohms per metre} & = & 0{\cdot}0202487 \\ \text{At } 15^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0215499 \\ \text{At } 30^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0228614 \\ \text{At } 60^\circ \text{ C.} \quad\quad\quad\;\; \text{,,} & = & 0{\cdot}0255148 \end{array}\right\} \begin{array}{c}\text{divided by} \\ \text{diameter} \\ \text{squared.}\end{array}$$

Example I.—To find the resistance at 60° C. (warm) of a copper strip 9·5 feet long, the rectangular section of which measured bare is 118 mils by 785 mils. The product of 118 and 785 gives as the sectional area 92630 sq. mils. Hence by the rule given above the resistance of one foot length is 9·4679 ÷ 92630 = 0·00010222 ohm. Therefore the resistance of 9·5 feet at this temperature is 0·000971 ohm.

Example II.—To find the resistance at 60° C. (warm) of a shunt coil of 3050 turns of a round copper wire, No. 16 S.W.G., the mean length of one turn being 5·21 feet. No. 16 S.W.G. has a diameter of 64 mils, therefore a sectional area of 64 × 64 (= 4096) circular mils. Hence by the rule the ohms per foot will be 12·0545 divided by 4096 = 0·002943 ohm. So the total length being 15890 feet, the total resistance will be 46·77 ohms.

The following rules are useful for copper wires at 30° C.:

Section in sq. mils = 10·8 × length in feet ÷ resistance in ohms.
Length in feet = section in sq. mils × resistance in ohms ÷ 10·8.
8483 ÷ section in sq. mils = resistance per 1000 feet of length.

Electrical Measurement of Temperature.—If the rise of temperature of an armature or of a field-magnet coil is measured at the surface by the common process of laying upon it the bulb of a thermometer covered with a pad of cotton wool, the temperature so measured will not be the true temperature of the interior, but considerably below the true average temperature of the armature or coil. If the resistance of the coil is measured, then the true internal temperature can be ascertained, provided the resistance of the coil at 0° C., or at 15° C. is known. For practical purposes a near enough approximation can be found by the formula:—

$$\text{Rise in degrees Centigrade} = 237\,\frac{R' - R}{R};$$

where R is the resistance as measured when cold, and R′ the resistance as measured when hot.

Stranded Copper Conductors.—Stranded copper wires are now seldom used in dynamo construction; but compressed stranded conductors are still occasionally found in smooth-cored armatures. An example is furnished by the toothed-cored armatures of the motors of the Central London Railway in which are employed conductors made of 49 strands of No. 19 B. and S. gauge, having an apparent cross section of 0·060 sq. inch. Now 1 such wire has a section of 0·00101 sq. inch, and 49 would therefore have 0·0495 sq. inches in total. But allowance must be made for the increased length due to twisting of the strands, and experiment shows the conductor to have such a resistance that its equivalent section would be only 0·046.

SPACE-FACTOR.

In all cases where insulated windings, whether of wire or strip, are used, it is obvious that the copper section in any slot or tunnel through the core disks does not occupy the whole of the space, and the fraction of the space occupied obviously depends upon the thickness of insulation, and upon the shapes of the slots and of the conductors. The ratio of the net cross-sectional area of the copper in a slot to the gross cross-sectional area of the slot is called the *space-factor.*

Space-Factor in Armatures.—The insulation within a slot consists of two parts: that which is employed as a lining to the slot to protect the iron from contact with the conductors, and that which surrounds the individual conductors to protect them from contact amongst themselves. The slot-lining must be relatively thick, because the iron core must be insulated from the full voltage of the machine, while the insulation around the individual conductors may be much thinner, as the difference of potential between any conductor and its neighbours will only be a small fraction of the full voltage. If every conductor had a slot to itself each slot must be lined with the thicker insulation; whereas if several conductors are placed in one slot, one stout lining will surround them all, and a larger fraction of the area of the slot will be filled with copper. The space-factor is therefore higher if the conductors are so grouped. In the lighting generator of Scott and Mountain (p. 582) working at 250 volts, the area of the slot is 0·65 square inch. The total area of section of the four copper conductors in the slot is 0·308, so that the space-factor is 0·473. Suppose the case of a conductor, the section of which was 500 × 150 mils, having therefore a sectional area of 75,000 square mils. Let this be overwound with thin insulating tape to a thickness of 15 mils, making the dimensions, covered, 530 and 180 mils: its gross sectional area will be 95,400 square mils. Now suppose that to insulate it properly from the iron core a paper and mica insulation 60 mils thick all round is necessary, the slot area for one such conductor must be obviously increased to 650 × 300 = 195,000 square mils at the very least. In practice it will be more, as there is usually a little extra space allowed for packing, and for a wedge under the binding wires. The space-factor cannot possibly exceed 0·395. But if four such conductors are put together, and the thicker insulation simply surrounds the group, the area of slot will have to be at least 1180 × 480 = 566,400 square mils, and the maximum space-factor will be raised to 0·529.

The space-factors in the armatures of some 500-volt machines are as follows:—Oerlikon Co.'s machines 0·6, 0·727, and 0·8; Parshall's 10-pole 0·6; Kolben's 6-pole and 10-pole 0·417 and 0·516; Ganz's 6-pole 0·412; Hobart's large generators 0·46, 0·49, and 0·51; Société Électricité et Hydraulique 0·404 to 0·510.

In a series of 550-volt generators designed by the late Prof. S. H. Short, ranging from 200 to 1100 kilowatts, the space-factor ranged from 0·423 to 0·533, with a mean value of 0·45.

Of machines at other voltages:—

Brown, Boveri and Co's. 350-volt, 0·32; 1000-volt (p. 753), 0·214; 120 volt, 0·505.
Thury's metallurgical machines (p. 717), 0·53 and 0·57.
Kolben's 4-pole at 260 volts, 0·506; 18-pole at 115 volts, 0·53.

Mr. Rothert states that in a series of 240-volt machines of all sizes, the space-factor of the magnet coils varied from 0·5 to 0·7.

In the case of high-voltage machines, particularly alternators, the space-factor is greatly reduced. The following example, due to Herr Kando, illustrates modern practice.

In Fig. 83 are shown three separate cases where slots of the same size are filled. In *a*, for a 500 volt machine there are 4 conductors each of 103·5 square mm. section; or in total 414 square mm. of copper. Each is separately surrounded with its own covering 1 mm. thick. The area of the slot is 668 square mm. So the space-factor is 0·63. In *b*, for 3000 volts there are 24 round wires, each 3 mm. in diameter, each also covered to a thickness of 1 mm. The slot lining must be about 4 mm. thick. The total section of copper is 170 square mm., and the space-factor has fallen to 0·25. In *c*, for 10,000 volts there are 80 wires, each 0·8 mm. diameter, with individual coverings 0·8 mm. thick. The slot-lining must be increased in thickness to about 6 mm. The total section of copper has fallen to 40 square mm.; and the space-factor to 0·06.

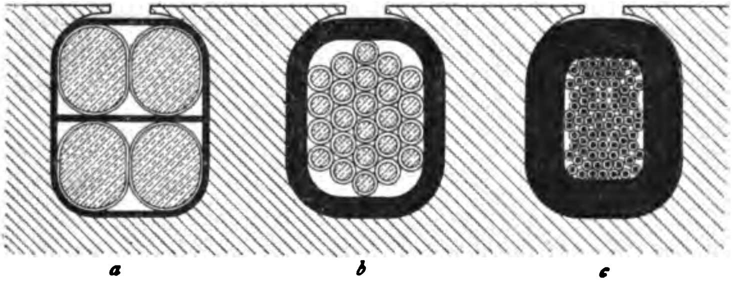


FIG. 83.—SLOT-SPACE AT DIFFERENT VOLTAGES.

Space-Factor in Field-Magnets.—In winding bobbins for field-magnets the space-factor is determined largely by the question whether round wires, or wires of square or rectangular section are used. In cases where rectangular wires are employed there is less waste space: and moreover there is a great gain in avoiding such waste space as that which fills the interstices between the wires, whether air or insulating material. Insulation is always a bad conductor of heat, and prevents the internally generated heat from escaping as quickly as it should. Of all non-conductors of heat, entangled air is the most perfect, witness the non-conducting properties of felt, eider-down, etc. Therefore square or rectangular wire should always be used if possible.

If round wires are used, the space-factor will be determined chiefly by the relative thickness of the wires and of their insulating covering; but it will also be affected by the question of the partial bedding of the wires of one layer between those of the layer beneath. Suppose the wires to lie in precisely square order, without bedding, as in Fig. 84; then if the diameter of the bare wire is d, and that of the wire covered is d_1, then since the area of each small circle is $0{\cdot}7854\,d^2$, and as the area of the small square enclosing the outer circle is d_1^2, the ideal space-factor would be

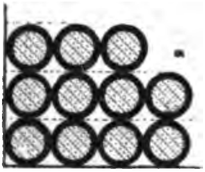


FIG. 84.
SQUARE ORDER OF BEDDING.

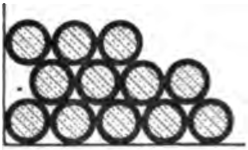


FIG. 85.
HEXAGONAL ORDER OF BEDDING.

$$\sigma = 0{\cdot}7854\,\frac{d^2}{d_1^2}.$$

Or, with an infinitely thin insulation it could never exceed 0·7854.

Suppose however an extreme case of bedding, as in Fig. 85, so that the wires lay in hexagonal order like the cells of a honeycomb, the space-factor then would be

$$\sigma = 0{\cdot}906 \times \frac{d^2}{d_1^2};$$

or with infinitely thin insulation would be 0·906.

If rectangular strip is used, uniformly covered, there is no bedding and no idle space save at the ends of a layer where the coil ascends to the next layer. If the breadth and thickness of the bare strip are called a and b, and when covered a_1 and b_1, the space-factor is simply $a\,b \div a_1\,b_1$. Edge-wound strip has the highest space-factor of any winding. Messrs. Ferranti find it to range from 0·83 to 0·93.

Now, in practice, there is with round wires very little bedding. Some writers have assumed 10 per cent., others 15 per cent. But this is far beyond the facts. Especially in the case of bobbins of small diameter the wire refuses to bed; since, as the successive layers are wound from right to left, and then left to right, each turn must at some point ride over a turn in the layer below it. Bedding, even in the hand of an experienced winder, seldom exceeds 3 per cent. The safest course is to assume that there will be no bedding at all and to take the space-factor, if not known from actual experience, as given by the formula above.

For the shunt-windings of dynamos of standard types at say 500 volts, the space-factor has values seldom below 0·45. This is the figure for the Scott and Mountain 6-pole machine, Plate V.; the Kolben 10-pole machine, Plate XVIII., has 0·60. Mr. Mavor gives values from 0·43 to 0·505 for the magnets of Mavor and Coulson dynamos.

Some actual figures are given by Dr. S. S. Wheeler for a number of different wires insulated to different thicknesses.

These are exhibited graphically in Fig. 86, the full curves representing the observed values, and the dotted curves the values by the formula assuming square order. It is seen that the larger sizes of wire do actually bed a little, giving a space-factor slightly higher than the calculated value.

Calculations of Bobbin-Winding.—The space-factor is closely connected with another important quantity, namely *the resistance per cubic inch of the winding.* By this expression is meant the total resistance of the winding divided by the number of cubic inches of volume which it fills. Suppose a wire covered to the thickness of 100 mils to be wound on a bobbin. There will be 10 wires side by side per inch length of the bobbin, and (if no bedding is assumed) there will be 10 layers per inch thickness, therefore, 100 wires through the square inch of cross-section. A cubic inch taken orthogonally (neglecting curvature) would therefore contain 100 wires each one inch long, and if these were joined in series with one another, the total amount of resistance within that cubic inch would clearly be 100 times the resistance per inch. If δ_1 be the diameter of the insulated wire, then $1 / \delta_1^2$ will be the number that go to a square inch of the winding section. Hence if we know the resistance per inch of the copper wire used, the resistance per cubic inch of the winding can be found

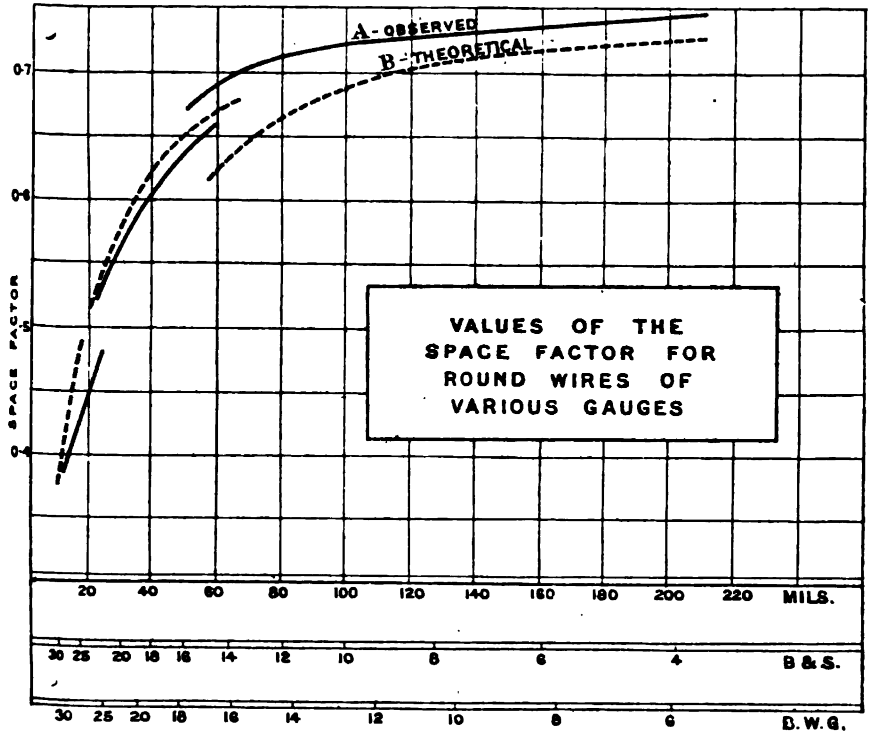


FIG. 86.—SPACE-FACTOR FOR WIRES OF DIFFERENT THICKNESSES.

by dividing it by the square of the diameter of the covered wire. If the diameter of the bare wire is given in mils, we have :—

Resistance per inch at 15° C = 0·8484 ÷ diameter squared.
„ „ 30° C = 0·9001 ÷ diameter squared.
„ „ 60° C = 1·045 ÷ diameter squared.

Or, if the diameter bare, d, and the diameter covered, d_1, be expressed in mils, *the resistance of one cubic inch of the winding* will be given by the formula:—

$$\rho_1 = \frac{0{\cdot}8484}{d^2 \times d_1^2} \text{ at } 15^\circ \text{ C.}$$

$$\rho_1 = \frac{0{\cdot}9001}{d^2 \times d_1^2} \text{ at } 30^\circ \text{ C.}$$

$$\rho_1 = \frac{1{\cdot}045}{d^2 \times d_1^2} \text{ at } 60^\circ \text{ C.}$$

This assumes, of course, square order in the winding, the space-factor in this case being $\frac{\pi}{4} \cdot \frac{d^2}{d_1^2}$.

If the number of turns of wire in the coil be S, and the area of the winding space be L × T, the number of wires through a square inch of the winding space will be S / LT. If we multiply the resistance per inch cube of copper by the square of this number, and divide by the space-factor we shall obtain the resistance of one cubic inch of the winding: or

$$\rho_1 = 0{\cdot}000000666 \frac{S^2}{L^2 T^2 \sigma} \text{ ohm at } 15^\circ \text{ C.}$$

$$\rho_1 = 0{\cdot}000000707 \frac{S^2}{L^2 T^2 \sigma} \text{ ohm at } 30^\circ \text{ C.}$$

$$\rho_1 = 0{\cdot}000000789 \frac{S^2}{L^2 T^2 \sigma} \text{ ohm at } 60^\circ \text{ C.}$$

It will be noted that *for a given number of turns of wire* in a bobbin of given winding space, the resistance per cubic inch, as well as the total resistance, will vary inversely as the space-factor.

Example.—A bobbin, of which the net winding-space is 10 inches long and 1½ inches deep, is to be wound with 540 turns of wire. Assuming a space-factor of 0·6, the resistance per cubic inch, at 60° C., will be $0{\cdot}000000789 \times 540 \times 540 \div (15 \times 15 \times 0{\cdot}6) = 0{\cdot}001704$ ohm. And if the mean length of one turn is 44 inches, the total volume will be $10 \times 1\frac{1}{2} \times 44 = 660$ cubic inches, making the total resistance 1·125 ohms.

To find the proper gauge of wire to fill a given bobbin to a prescribed resistance.—Dividing the prescribed resistance by the volume of the winding space, one obtains the number of ohms per cubic inch. Reference to a table of wires with various thicknesses of covering for which the values are known, will enable the proper gauge to be picked out. For such *Wire-Gauge Tables* see the Appendix. This case arises in series motors, where the permissible resistance depends on the number of watts which the coil can radiate (see p. 183). Dividing the permissible watts by the square of the current gives the resistance.

Example.—A certain coil of volume 4300 cubic inches is to carry 50 amperes, the permissible watts being 220. Then $220 \div 2500 = 0{\cdot}88$ ohm. Hence the resistance per cubic inch of the winding will be $0{\cdot}88 \div 4300 = 0{\cdot}000202$ ohm. The Wire Gauge Tables show that the nearest sizes are No. 3 S.W.G., with 0·00018, and No. 4 S.W.G., with 0·000248. Therefore we must take No. 3 gauge.

To find the proper gauge of wire to carry a given current.—One may also estimate the gauge of the wire required by knowing what is a suitable ampere-density. In stationary coils a density of 600 to 900 amperes per square inch is customary. (This is roughly from 1 to 1½ amperes per square millimetre.) Otherwise stated, one allows from 1100 to 1666 square mils per ampere, or 1400 to 2100 circular mils per ampere.

Example.—Estimate the gauge of wire required for 6 amperes. The wire, at 600 amperes per square inch, will require $\frac{1}{100}$ of a square inch or 12,566 circular mils section. Reference to wire gauge tables shows that the nearest size is a No. 11 S.W.G., which has a section of 0·0105 square inch, or 13,200 circular mils.

In small machines the current-density in the shunt-winding may safely exceed 1000 amperes per square inch, and even attain 1400. In the Scott and Mountain generators (p. 663) it varies from 660 to 1360.

Given the ampere-turns, the volts, and the mean length of one turn, to find the *gauge of the wire*, the *resistance*, the *number of turns* and the *volume.*

This case derives its importance from its use in calculating *shunt windings.* Let the prescribed number of ampere-turns be called CS, neither C nor S being separately known. Let the volts applied to the terminals of the bobbin be V, and let M denote the mean length of one turn. (In many cases this will be only approximately known at first.) Let r_1 stand for the resistance per inch length, as given in the Wire Gauge Tables. Now the resistance R of the coil may be expressed in two different ways:

$$R = \frac{V}{C} = M r_1 S \quad . \quad . \quad [1]$$

and further

$$M r_1 CS = V,$$

whence

$$\frac{V}{(CS)M} = r_1 ; \quad . \quad . \quad . \quad . \quad [2]$$

which fixes the gauge.

Professor Crocker has given the useful rule:—

$$\text{Circular mils} = \frac{(CS) \times M}{V} \times 12 \cdot 25 \quad . \quad [2a]$$

Example.—A shunt dynamo with 8 coils in series, working at 200 volts, requires 5200 ampere-turns of excitation per pole. The pole cores are circular of 10 inches diameter: the winding is expected to lie about 3 inches deep; whence internal diameter of windings will be about 11 inches, external about 16, so that the mean length of 1 turn will be about 42·5 inches. Then V = 25; CS = 5200; M = 42·5; whence r_1 = 0·0001131 ohms per inch. This is equal to 0·0013572 ohms per foot or 1·357 ohms per 1000 feet. Referring to the Wire-Gauge Table in the Appendix we observe that the nearest larger size is a No. 12 S.W.G., which (at 60° C.) has a resistance of 1·114 ohms per 1000 feet.

If a square wire is to be used, the area in square mils may be found by dividing 0·79 by the number of ohms per inch calculated as above.

The gauge having been found, let a suitable thickness of insulation be fixed upon and the resistance per cubic inch ρ_1 be ascertained. It may be noted that *if square order of winding be assumed* then $\rho_1 = \omega \div d_1^2$; where d_1 is the diameter of the covered wire in mils: but ρ_1 is best taken from actual tables of windings that have been carried out. If ρ_1 is thus known, $\rho_1 \times$ volume $=$ R. If the volume of the coil is given this settles the resistance,[1] and if R is thus ascertained dividing it by Mr_1 gives the number of turns S. Or dividing R by r_1 gives the total length required for the coil.

If the volume of the coil is not prescribed beforehand we must work from other data. Suppose the *number of watts that may be wasted in heating* is given. (This may be estimated (*a*) as a percentage of the whole output, see p. 552; or (*b*) from the estimated available cooling surface and the permissible rise of temperature, see p. 183.) Call the watts that will be wasted in heating the coil W. Then

$$W = VC = C^2R = V^2/R \quad . \quad . \quad [3]$$

$$\text{and as } R = \rho_1 \times \text{volume}$$

it follows that

$$\text{volume} = \frac{V^2}{\rho_1 W} = \frac{V}{\rho_1 C} \quad . \quad . \quad [4]$$

From this we see that the volume can be calculated if either the watts or the current are prescribed.

If the permissible temperature is also prescribed, this (see p. 183) fixes the permissible number of watts per square inch of cooling surface; and this latter being settled, determines the number of square inches of surface that the coil must have. If the coil as designed proves to have an insufficient surface, then it must be re-designed so as to have a longer length, or else the volume of the whole must be increased, and a greater weight of copper used; and if new dimensions are thus chosen a new value must be taken of the mean length of one turn, and the computation repeated.

It must be ever borne in mind that in shunt windings, if the mean length of one turn is prescribed, and a given number of ampere-turns is prescribed, everything depends upon the resistance per turn, and therefore *on the gauge*. Suppose a shunt winding to have 1000 turns, it will have a certain resistance, therefore at the prescribed voltage takes a certain current producing a definite number of ampere-turns. Now suppose that half the windings are cut out, while preserving the same mean length per turn. The remaining 500 turns will offer half the resistance, and will therefore receive twice as much current as before, bringing up the ampere-turns to the previous value; but the C^2R loss will have been doubled. Increasing the length of a shunt bobbin while preserving the same depth of winding and same gauge of wire, will therefore enable the required excitation to be obtained with a lessened waste of energy.

---

[1] See also formulæ by Löwit in *Elektrot. Zeitschr.*, xxi. 881, 1900.

If the volts, heat-loss, the watts per square inch, mean length of one turn, and resistance per cubic inch are all known the length L of the bobbin (in inches) can be found from the formula

$$L = \left(M\frac{W}{\xi} - \frac{\pi V^2}{\rho_1 W}\right) \div M^2; \quad . \quad [5]$$

where W is the number of watts of permissible heat-loss, and ξ the permissible number of watts per square inch, dependent on the permissible temperature rise.

Another way of calculating the gauge of the wire from the ampere-turns, the volts, and the mean length of one turn, is as follows:—Let k be the resistance of a wire 1 inch long and 1 mil in diameter (= 0·9 ohms at 30° C.), then

$$R = \frac{V}{C} = k\frac{SM}{d^2},$$

where d is the diameter in mils. We may deduce:—

$$d = \sqrt{\frac{kCSM}{V}} \quad . \quad . \quad . \quad [6]$$

Example.—Taking, as in the former example, V = 25; C S = 5200; M = 42·5; and taking k = 0·9, the formula gives d = 89·2 mils, which is between Nos. 13 and 14 S.W.G. If we had taken the temperature as 50° C., we should have had k = 0·972, and d = 92 mils, which is almost exactly No. 13 S.W.G.

If square order in the winding be assumed, the number of turns in one layer and number of layers, occupied by a coil of S turns of external diameter d_1 mils, having a net length of winding space L (inches), can be calculated from the following formulæ:

$$\text{No. of turns in 1 layer} = 1000\,L \div d_1.$$
$$\text{No. of layers} \quad " \quad = S d_1 \div 1000\,L.$$

Hence the radial depth or thickness T of the coil would be

$$T = S d_1 \div 1{,}000{,}000\,L\,;$$

but owing to bedding, T will probably come a little less than this. Further, it is not safe to assume without trial that the number of turns in one layer can be found by the formula from a measurement of d_1 made with callipers. The right way is to try by winding a piece of coil with the wire in question. A few turns may be wound on a wooden core and the length occupied by 10 turns should be accurately measured, and divided by 10 to find the working value of d_1.

Curves to facilitate calculations for magnet winding have been given by Mr. H. H. Wood in the *Electrical World*, xxv. pp. 503 and 529, April 1895.

The following rules, due to Mr. Kapp, give the *weights* of copper in coils, W standing for the permissible number of watts wasted, D the mean diameter in inches, M the mean length of one turn in inches (for coils not circular in shape), and CS stands for the prescribed number of ampere-turns of excitation.

$$\text{Weight in lbs.} = 2{\cdot}4 \times 10^{-6} \times \frac{(CS)^2 D^2}{W}\,; \quad . \qquad [7]$$

$$\text{weight in lbs.} = 0{\cdot}245 \times 10^{-6} \times \frac{(CS)^2 M^2}{W}\,. \quad . \qquad [8]$$

COIL WINDING.

Coils for field-magnets may be classified as (*a*) *bobbin-wound*, (*b*) *former-wound*. In those wound on bobbins no special instructions are needed, except as to modes of fixing and bringing out the ends. Rectangular wire is preferable in every case where the wire is to be wound to a radial depth exceeding one inch, as it gives a much better space-factor than round wire. Better still is edge-strip winding where it can be used.

Field-magnet Bobbins.—These are made variously of brass with brass flanges, of sheet iron with brass flanges, of very thin cast iron, sometimes even of zinc. Some makers use sheet metal with a flange of hardwood, such as teak. The reader should examine the examples given in the following pages: in particular the Scott and Mountain machine (p. 665, Plate V.); the Kolben machine (p. 671, Plate XVII.); and the English Electric Manufacturing Co.'s machine (p. 694). Ample pains must be taken to line the bobbin with adequate insulating materials such as layers of press-spahn, vulcanized fibre, or varnished mill-board. Great attention must be paid to the manner of bringing out and securing the inner end of the coil. If a bobbin is simply put upon a lathe to be wound, the inner end of the wire, which must be properly secured, requires to be brought out in such a way that it cannot possibly make a short-circuit with any of the wires in the upper layers as they cross it. A method of winding which obviates all difficulty on this score is to wind the coil in two separate halves, the two inner ends of which are united, so that both the working ends of the coil come to the outside. Fig. 87 shows such a bobbin. The windings are secured by bindings of tape. This method of construction has been used for years in winding the secondaries of induction coils, where it is desirable to keep the ends of the winding away from the iron core and from the primary coil.

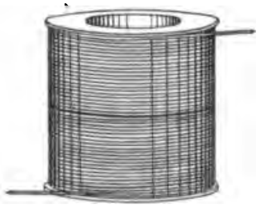


FIG. 87.—BOBBIN WITH BOTH ENDS AT OUTSIDE.

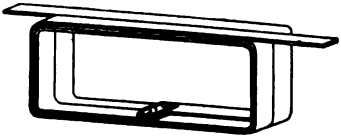


FIG. 88.—STRIP-WOUND COIL.

Mr. C. E. L. Brown introduced a method (Fig. 89) of piling up the windings conically, without any end flanges, thus avoiding some of the risks of breakdown; and for high voltage work he adopted the plan of similarly piling the windings into two heaps (Fig. 90), so that both the free ends come at the outside.

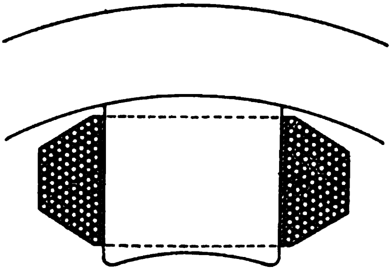


FIG. 89.—BROWN'S PILED COIL.

In winding copper strip for the coils of tramway motors a similar device has been resorted to; the union of the two strips being effected at the interior of the coil as in Fig. 88.

In another form of machine, by Messrs. Alioth, the pole cores, which are removable, are themselves shaped to serve as bobbins, and, after being served with a protecting layer of insulation, are wound in the lathe. This is shown in Fig. 91.

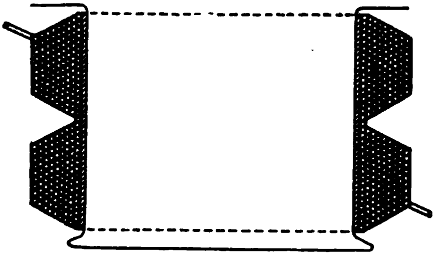


FIG. 90.—BROWN'S PILED HIGH-VOLTAGE COIL.

Former-wound Coils are wound upon a block of wood to which temporary checks are secured to hold the wires together during winding.[1] Such coils have pieces of strong tape wound in between the layers and lapped at intervals over the windings so as to bind them together. For tramway motors, which are subject to excessive vibration, very strong tapes must thus be woven in; and the completed coil is served with two layers of tape each separately soaked in insulating varnish. The whole coil is then soaked with insulating varnish and stove-dried. Preferably a current is sent through the coils to heat them internally while they are being baked. They thus become thoroughly mummified and hard. For such motors an asbestos insulation is sometimes prescribed. All field-magnet coils, whether bobbin-wound or former-wound, ought indeed to be thoroughly soaked with varnish and stove-baked.

---

[1] For an illustrated account of the use of former-blocks in winding, see the *Electrical Engineer* (London) for May 1902.

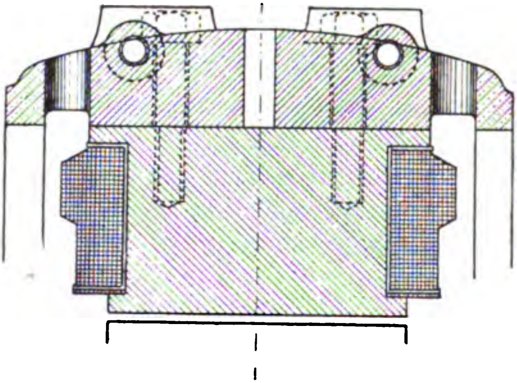


FIG. 91.—WOUND POLE-CORE (Alioth).

Bringing out and Fixing of Ends.—Figs. 92 to 94 illustrate methods used for bringing out the ends of coils. In Fig. 92 copper strip, laid in behind an end-sheet of insulating material, makes connexion to the inner end, as shown in the upper side of the figure, while another strip, shown in the under side similarly inlaid, serves as a mechanical as well as an electrical attachment for the outer end of the winding. This device is due to Mr. Kapp.

Another method, due to Messrs. Ganz and Co., is illustrated in Figs. 93 and 94.

A simple device for securing the outer end is to fashion a terminal piece like Fig. 95 so that it can be laid upon the windings, the last three or four turns of which are wound over its base, and after winding are bared at the place and soldered securely upon it.

Insulation of Field-Magnet Coils.—It is not absolutely necessary to use any mica preparation for insulation of field-magnet bobbins, several layers of paper preparations being more often used. One-tenth of an inch thickness, if made up of several superposed layers, is generally adequate. Varnished canvas is useful as an underlay, and press-spahn or vulcanized fibre for lining the flanges. It is important to protect the joint between the cylindrical part and the flanges. As an example of careful insulation, may be cited the method adopted at Schenectady for insulating the magnets of the Edison bipolar machines, working at 100 to 125 volts, which are insulated as follows: End-rings of hard rubber are wedged upon the iron cores with mica. When bits of sheet mica are used, these are cut to be 1½ inch wide and at least 3 inches long ; but when "made mica" sheets are used, long strips 5 inches wide are cut, and conformed by heating to the curvature of the core. In either case the mica projects at least 1 inch on the inner side of the ring. Then over the core is laid one layer of varnished muslin 24 mils thick, cut to the exact width between the end-rings. Upon this are placed two layers of plain pressed

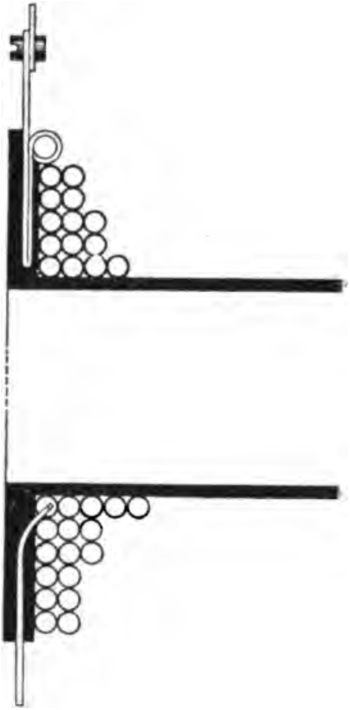
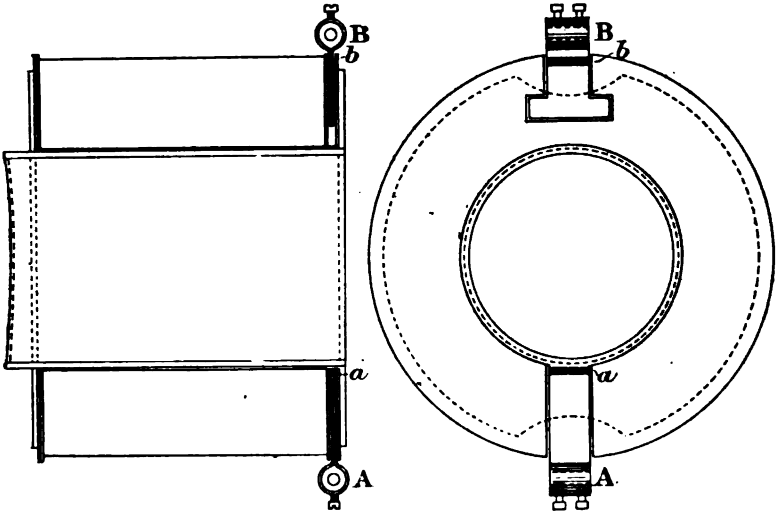


FIG. 92.—MODE OF BRINGING OUT ENDS.

board 20 mils thick, cut one inch wider than the width between the end-rings, and serrated with V-cuts ⅛-inch deep at its edges, so as to allow these edges to make flanges against the end-rings, the serrations of the two layers breaking joint one with the other. The total thickness of core insulation is thus 64 mils. A core-paper is laid between every four layers of winding. Between series and shunt coils, in compound-wound machines there is as careful an insulation as on the cores. When the winding is completed two layers of pressed board are laid over, and served with an external winding of hard rope, and varnished.



FIGS. 93 AND 94.—METHOD OF BRINGING OUT ENDS (Ganz).

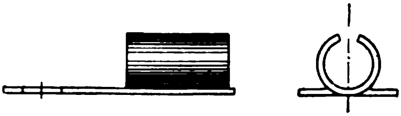


FIG. 95.—COIL TERMINAL PIECE.

For machines up to 250 volts, 4 layers of oiled pressed board are used over the muslin.

For machines up to 500 volts or more, 3 layers of oiled linen 5 mils thick, not turned up at edges, are placed over the muslin. Over these come first four layers of oiled pressed board, and then two layers of plain pressed board, the latter with edges serrated to form flanges. This makes a total thickness of insulation 159 mils. Core-papers are laid between every three layers of winding, and three layers of pressed board are served on the outside.

The protective external lagging covering the outer surface of the completed coils is not altogether a benefit, for it tends to prevent dissipation of heat.

Attachment of Magnet Coils.—The usual mode of supporting the magnet coils is by means of the projecting pole-shoes; these are sometimes made removable, or if solid with the pole-core, the latter is made removable from the yoke. Some machines have no pole-shoes, and in this case means must be taken to support the coils. Small side brackets screwed into or bolted through the projecting end of the pole-core are used. Another method is to provide triangular blocks of hard-wood, which lie in the space between the pole tips of two adjacent poles, and are secured by long bolts to the yoke, as indicated in Fig. 96. Fig. 97 shows the plan adopted in the traction motors of W. Lahmeyer and Co.

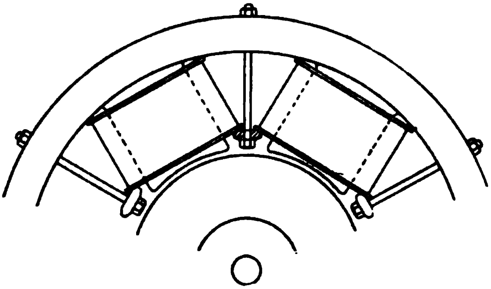


FIG. 96.—MODE OF ANCHORING COILS.

Connexion of Magnet Coils.—The almost invariable plan of connecting magnet coils is to unite them in series, so that the same magnetizing current may flow through them all. This is the case for separately excited, and for shunt-wound machines. They must be connected up so as to secure that they produce alternate north and south poles. If all the coils are similarly wound with respect to the terminals, and similarly placed, that is to say so placed that the winding, considered from the coil terminal nearest the pole-face, starts in all the coils in the same direction (i.e. all right-handedly, or else all left-handedly) then the connexions will come alternately at the pole face end, and at the yoke-end of the bobbins. (Compare the plates at the end of this book. See in particular the Kolben machine, Plate XVI.). The compounding coils should be similarly connected in series amongst themselves.

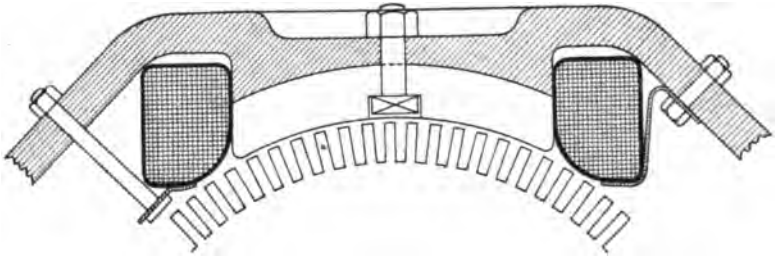


FIG. 97.—MODE OF SUPPORTING COILS.

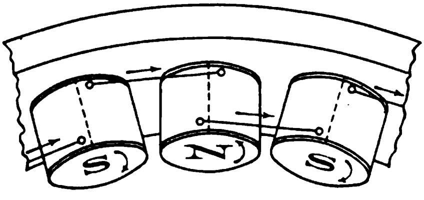


FIG. 98.—CONNEXIONS OF FIELD-MAGNET COILS.

In the case also of series-wound machines, such as tramway motors, the whole of the magnet bobbins should be in series.

Ventilation of Field-Magnet Bobbins.—It is not usual to ventilate the bobbins of field-magnets ; but in some cases, as for example the magnet-wheels used for alternators, some makers design the bobbins to be of greater length (parallel to the shaft) than the length of the pole-core, thus affording wind-ways. Also the series coils of compound-wound generators are sometimes supported away from the shunt-coils, with air-ways between them.

Heating of Coils.—The heat inevitably generated in the copper coils is dissipated in two ways. It passes by conduction through the copper and the insulation, either to the external surface, whence it passes off by radiation and convexion into the air, or to the magnet-core and yoke, which in turn conduct it away and dissipate it from their surfaces. In large multipolar machines the masses of metal in the pole-cores and magnet-frame are more efficacious than the external surface of the coil in dissipating the heat.

Some considerations in general concerning the heating of coils may here be discussed. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire upon which it is wound, it follows that the weight of copper in a coil filling a bobbin of even dimensions will be the same, whether a thick wire or a thin one be used. Further, for a given volume to be filled with coils, the resistance in ohms of the coil will vary directly as the square of the number of turns in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of a wire having half the sectional area, the resistance of the new winding will obviously be four times as great as that of the original winding. Also by a similar argument, it follows that the resistance of a coil of given volume will vary ***inversely as the square of the sectional area*** of the wire used. And as the area is proportional to the square of the diameter of the wire, it follows that the resistance is ***inversely proportional to the fourth power of the diameter*** of the wire used.

The amount of heat developed per second in a coil is the product of the resistance into the square of the strength of the current. To avoid waste, therefore, no unnecessary resistance should be introduced into any main-circuit coil. It is easy to show that with a coil of ***given volume***, the heat-waste is the same for the same magnetizing power, no matter whether the coil consists of few windings of thick wire or many windings of thin wire. The heat per second is $C^2 R_M$, and the magnetizing power is S C; C being the current, R_M the resistance, and S the number of turns. But R_M varies as the square of S, if the volume occupied by the coils is constant. For suppose we double the number of coils, and halve the cross-sectional area of the wire, each foot of the thinner wire will offer twice as much resistance as before; and there are twice as many feet of wire. The resistance is quadrupled therefore. The heat is then proportional to $C^2 S^2$: and therefore the heat is proportional to the square of the magnetizing power. If, therefore, we apply the same magnetizing power by means of the coil, the heat-waste is the same, however the coil is wound. To magnetize the field-magnets of a dynamo to the same degree of intensity requires the same expenditure of electric energy, whether they are series-wound or shunt-wound, *provided the volume is the same, and the space-factor is unaltered.* Any increase in the space-factor is equivalent to a larger volume, or to the discovery of a wire having a lower specific resistance. With a higher space-factor the prescribed excitation can be attained with a lesser waste of energy. This is the reason for the advantage of using square wire or strip winding instead of round wire.

A simple way of looking at this matter is to regard the whole winding as consisting of one turn, there being a current, equal to the total ampere-turns, going only once round. Then this current divided by the total cross section of copper gives the current-density. We then see that for equal-sized bobbins (containing the same amount of copper) the magnetizing effect is simply proportional to the current density. Further, the power wasted per lb. of copper is proportional to the square of the current-density. The following Table XI. gives the waste in watts for different current-densities in both inch and centimetre measure. The temperature of the coil is taken at 30° C., at which temperature the resistance of an inch cube of copper may be taken at $0{\cdot}7 \times 10^{-6}$ ohm.

If the *volume* of the coil (and the weight of copper in it) may be increased, then the heat-waste for a given magnetizing force may be proportionally lessened. For example, suppose a shunt-coil of resistance r has S turns ; if we wind on another S turns in addition, the magnetizing power will remain nearly the same, though the current will be cut down to one-half owing to the doubling of the resistance ; and the heat-loss will be halved, for $2\,R_M \times (\frac{1}{2}\,C)^2$ will be $\frac{1}{2}\,C^2\,R_M$.

TABLE XI.—LOSS OF POWER IN COPPER CONDUCTORS AT DIFFERENT CURRENT-DENSITIES.

Current-Density.		Watts converted into Heat.		
Amperes per sq. in.	Amperes per sq. cm.	Per cubic in. of copper.	Per cubic cm. of copper.	Per lb. of Copper.
400	62	0·112	0·0068	0·548
500	77·5	0·175	0·0106	0·544
600	93	0·252	0·0154	0·784
700	108·5	0·340	0·0204	1·057
800	124	0·448	0·0273	1·393
900	139·5	0·567	0·0340	1·758
1000	155	0·7	0·042	2·17
1500	232	1·57	0·096	4·88
2000	310	2·8	0·171	8·71
2500	387	4·37	0·266	13·59
3000	465	6·3	0·384	19·59
3500	542	8·5	0·510	26·43
4000	620	11·2	0·683	34·83

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of wire that economy dictates, new cores should be designed having a sufficient length to receive the wire which is economically appropriate.

In order then that any coil (whether upon the armature or field-system) may not overheat, it must have sufficient surface relatively to the amount of heat developed in it by the current. For equal watt loss per unit area of radiating surface, the amount of heat developed will be entirely different in field-magnets and armatures, on account of the different conditions under which the heat is liberated, and consequently we must consider them separately.

Heating of Field-Magnets and Stationary Bobbins generally.

Let w_m be the total watts wasted in the field-coils at full load, that is, $w_m = (C^2_M R_M + C^2_S R^2_S)$.

A_1 be the total heat-radiating area of all the bobbins, in square inches, not counting end flanges and internal surfaces (if any).

θ_m represent the final temperature rise above the surrounding air.

Then

$$\theta_m \propto w_m,$$

and

$$\theta_m \propto \frac{1}{A_1};$$

or

$$\theta_m = \frac{w_m}{A_1} \times h$$

The value of the constant h depends upon the depth of winding, upon the amount of the draught set up by the fanning action of the armature, and upon the condition of the air, that is, circulating or still. According to Mr. W. B. Esson, the value h may be taken as 55 for ordinary field bobbins. That is to say, an emission of wasted heat at the rate of 1 watt per square inch will cause a rise of 55° C.; or, if 30° C. be taken as the permissible amount of rise, the coil must expose 1·83 square inches per watt wasted in it. This figure appears to be low for modern machines. The temperature is here assumed to be measured by thermometer at the surface of the coil, covered with a pad of cotton-wool. For the usual shape and dimensions of field-bobbins, more particularly those of multipolar machines other than iron-clad types, the formula

$$\theta_m \text{ (in Centigrade degrees)} = \frac{w_m}{A_1} \times 75 \quad . \quad [9]$$

will be found to give good results. The value of the heating constant is higher for iron-clad types and enclosed motors.

For shunt-bobbins this formula gives directly the maximum shunt current C_M that may be used if the temperature rise is prescribed as a limit. Thus

$$w_m = V \times C_M = C_M^2 R_M$$

$$C_M = \sqrt{\frac{\theta_M \times A_1}{75 \times R_M}} . \quad . \quad . \quad . \quad [10]$$

Or, if the excitation watts and temperature rise are given, we have for the necessary radiating surface of the coils

$$A_1 = \frac{75 \times w_m}{\theta} . \quad . \quad . \quad . \quad . \quad [11]$$

In the case of *edge-strip coils* being used, the temperature rise will be much less than that calculated by these formulæ, because in coils of this species the internally-generated heat is conducted much better to the surface, whence it escapes without the internal temperature rising so high. Messrs. Ferranti found the temperature rise after 6 hours in a 1500 kilowatt machine at 150 revs. per min. to be only 16 deg. C., though the current-density was 920 amps. per sq. inch. In a 150 kilowatt machine at 380 revs. per min., and 1200 amps. per sq. inch, the temperature rise was only 14·5 deg. C. after 6 hours. In one case where an edge-strip winding was in two layers with insulation between, though the current-density was only 800 amps. per sq. inch, the rise was about 28 deg. C. after a 5 hours' run.

At the Oerlikon Works, a limit of 30 deg. C. assigned to the heating of a stationary bobbin, is found to correspond to an emission of 0·4515 watts per square inch : or 2·2 square inches of radiating surface are necessary for getting rid of each watt wasted in heating. This makes the constant $h = 66$.

If we assume that a limit of temperature rise of 50 deg. C. above that of the surrounding air is safe, then the largest current which may be used with a given stationary magnet coil, is expressed by the formula—

$$\text{Maximum permissible current} = 0{\cdot}95\sqrt{\frac{A}{R_M}}.$$

Similarly, for *shunt coils* we have

$$\text{Maximum permissible voltage} = 0{\cdot}95\sqrt{AR_M}.$$

Some recent measurements of the rise and distribution of temperature in field-magnet coils have been made by E. Brown,[1] and by Neu, Levine and Havill.[2] Brown's observation made on a bipolar Siemens dynamo led him to note how efficacious in promoting cooling was the metal in proximity. He recommended that the bobbin-heads should be made as good conductors of heat as possible; that any gap between the pole-core and the bobbins should, if possible, be filled up with good conducting material; and that, as bobbins heat most at the mid-length they should be made of less depth there, that is of an hour-glass form. The Electric Construction Company undulates (see Fig. 445) the profile of its field-coils for the purpose of better cooling. Messrs. Neu, Levine and Havill, using a bipolar Crocker-Wheeler motor, explored the distribution of temperature throughout the cross-section of the coils, by electrical measurement of the rise of resistance of the various parts of the winding, and also measured the apparent rise of temperature with thermometers. They plotted isothermal curves showing how under varying conditions the temperature is distributed, when the coil was, (1) supported in the air, (2) standing on a table, (3) in place on the machine at rest, (4) in place on the machine running at full load: in each case the coil being heated for six hours at the rated voltage. The first case showed the greatest heating, for, though the table arrested the circulation of air it seemed to cool the whole coil. The average rise in the four cases was 37·5, 33·9, 22·7 and 28·3 deg. C. respectively. In case 3 the iron core conducted away more heat than the external air, the point of maximum temperature being nearer to the surface than to the core. They observed with the machine running at full load, a rise of 110 deg. C. *per watt per square inch of exposed cylindrical coil surface*; and with the machine stationary, a rise of 100 deg. C. This makes the formula—

---

[1] *Journal of the Inst. of Elec. Engineers*, xxx. 1159, 1901.

[2] *Electrical World*, xxxviii. 56, July 13, 1901.

$$\theta_m \text{ (in Centigrade degrees)} = \frac{W_m}{A_{cyl}} \times 110, \qquad [12]$$

leading to the result that if the limit of rise be set at 30 deg. C. there must be allowed no less than 3·66 inches of cylindrical surface per watt wasted in the magnet coil. It appeared that a surface exposed to contact with iron was nearly twice as efficacious as a surface exposed to air, leading to the rule :—

$$\theta_m \text{ (in Centigrade degrees)} = 340 \frac{W_m}{A_a + 1{\cdot}875\,A_i} \qquad [13]$$

where A_a is the area exposed to air and A_i that in contact with iron.

They found the true mean rise of temperature as measured by increase of resistance to be 1·4 to 1·6 or more times as great as the apparent mean rise measured by thermometer.

Some calculations about the greater heating of interior layers have been given by Joyce in *Journ. Institution Electrical Engineers*, xix. 248, 1890.

In the case of enclosed motors, without any resort to artificial cooling, it is difficult to prevent the internal temperature from rising by as much as 100 deg. C. above that of the surrounding air. Some makers provide their enclosed motors with external radiating ribs to aid dissipation of the heat. For these the temperature-rise (according to Niethammer) may be reckoned as equal to about 95 to 140 times the total watts lost divided by the *total* surface, in square inches, that is exposed to the circulation of air.

Heating of Armatures or Running Coils.—The amount of heat liberated in a rotating armature depends principally upon :—

(1) The heat-radiating surface A_2. In estimating this, the number of square inches exposed to the cooling action of the air are to be taken, but it is a matter of discretion to estimate what proportion of the internal surfaces contribute to it.

(2) The peripheral speed v of the winding. For small armatures and ring winding the average peripheral speed (feet per minute) as given by the average diameter of the armature, is to be taken.

(3) The proportion, within limits, of radiating surface to polar surface. Naturally, an armature nearly covered by the pole-pieces will not have, as a rule, such a good chance of getting rid of the developed heat, as one whose radiating surface is more open to the air.

The heating of an armature in which w_a total watts (iron and copper losses) are being wasted can be estimated from the formula

$$\theta_a = \frac{w_a}{A_2} \times \frac{a}{1 + (b \times v)} \quad . \quad . \quad . \quad [14]$$

where a and b are constants—the values of which are dependent on the type of machine.

The constant a varies in ordinary well-ventilated machines of modern design from 50 to 90, while constant b appears to vary from 0·0004 to 0·0009, if v is in feet per minute. The curves given in Fig. 99 are, however, more convenient to employ for estimating the temperature rise, as representing what is usually found in modern practice. The ordinates represent the rise of temperature per watt per square inch and the abscissæ the peripheral speeds. Curve A A is to be used for small unventilated armatures, and is based upon the average results of Messrs. A. H. and C. E. Timmermann,[1] and with tests made upon actual machines. Curves B B and C C are to be used for estimating the temperature rise of small well-ventilated armatures and large ventilated armatures more or less of a fly-wheel nature, respectively.

---

[1] *Trans. Amer. Inst. Electr. Engineers*, x. 1893.

Hence to find the temperature rise θ_a of any armature running at a peripheral speed of v feet per minute: Divide the number of watts wasted by the number of square inches,

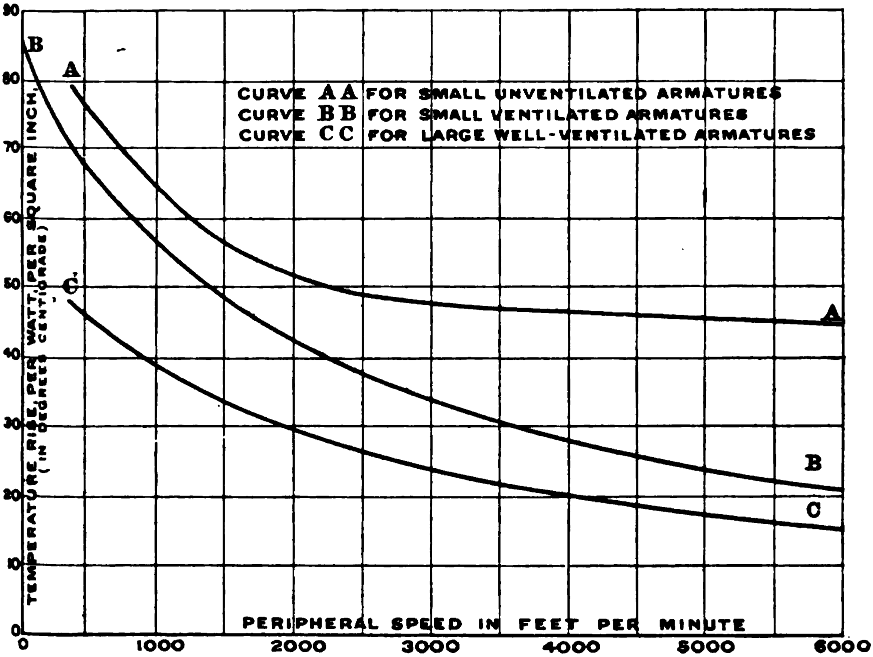


FIG. 99.—CURVES FOR ESTIMATING TEMPERATURE RISE.

and then from one or other of the curves find the temperature rise corresponding to the peripheral speed in question.

At the Oerlikon Works, it was found that, taking a surface speed of about 2000 feet per second, and a permissible temperature rise of 30° C., each square inch of armature surface (external) could dissipate from 1·29 to 1·61 watts; or each watt requires from 0·6 to 0·8 square inch. Assuming 4 per cent. of the output to be wasted in armature heat, or 40 watts per kilowatt, the necessary armature surface must therefore be about 24 to 32 square inches per kilowatt of output.

Owing to the cooling effect of the air-currents when the armature is running it is found that when a dynamo is stopped at the end of a long run, the surface temperature immediately rises above what it was when the machine was running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. Thus we find that in Admiralty specifications it is laid down that after the end of a run of six hours at full-load, no accessible part of the armature or field-magnets shall show a greater rise than 70° F. (= 38·8° C.) above the surrounding air. This does not by any means imply the final temperature rise, because the thermometer will invariably continue to rise for a much longer period than one minute. But in any case this temperature limit is needlessly low, as a rise of twice as much would be perfectly safe, even in the hottest engine-room.

CHAPTER VIII.

INSULATING MATERIALS, AND THEIR PROPERTIES.

INSULATING materials other than air and the gases may be classified under several heads :—

(i.) *Vitreous*, including glass, enamel, "vitrite," and sundry kinds of slags.
(ii.) *Stony*, such as slate, marble, steatite, mica, asbestos, kieselguhr, stone-ware, porcelain, "petrifite."
(iii.) *Osseous*, such as bone and ivory.
(iv.) *Resinous*, including shellac, resins of all sorts, copal and other gums.
(v.) *Bituminous*, as bitumen, asphaltum, pitch.
(vi.) *Waxy*, including bees-wax, solid paraffin, ozokerit, and the like.
(vii.) *Elastic*, such as indiarubber, natural and vulcanized, ebonite, gutta-percha.
(viii.) *Oily*, including various oils and fats of animal and vegetable origin, as well as mineral petroleum.
(ix.) *Cellulose*, including dry wood and paper; many natural substances, such as cotton, wood pulp, and many preparations of paper and of wood pulp, papier-mâché, press-spahn, manila-paper, vegetable parchment, "vulcanized fibre," celluloid, "Willesden paper."
(x.) *Silk*, and allied animal tissues such as catgut.
(xi.) *Sulphur*.

From these materials, or some of them, there are now manufactured a number of artificial preparations known under trade names, such as "ambroin," "megohmite," "stabilit," "micanite," "vulcabeston," oiled-paper, "empire cloth," insulating tape, and kindred fabrics; also special varnishes, such as "armalac," "japan," "enamelac," "Sterling varnish," and "Scott's rubber varnish."

Dielectric Resistance.—All insulating materials are mechanically bad. They differ enormously in their specific electric resistance, and in their power of resisting penetration by a spark. They all share the particular property that as their temperature is raised their electric resistance decreases enormously, and in general they become fairly good conductors so soon as any chemical change begins. Even marble, glass and porcelain begin to conduct as electrolytes below a red heat. Some are liable to absorb moisture from the atmosphere and so lose their insulating properties.

The most important thing to know about such insulating materials as are used in dynamo construction is their power to resist being pierced by a spark. It is also important to know whether they are hygroscopic, whether they are impaired when their temperature is raised, and whether they deteriorate with time.

Porcelain and stoneware are used for insulating bushes, and as supports for terminals. Dry wood and paper preparations such as press-spahn, vulcanized fibre, papier-mâché, oiled canvas and the like are only used for low voltages, or as secondary insulators, that is insulators which, while mechanically holding the conducting parts apart, form a backing for some better primary insulator such as mica.

Experimental data as to the *dielectric strength* of insulating materials have been made from time to time by various authorities. From these the following have been collected. Fig. 100 relates to layers of *pure mica* and of *oiled canvas* of different thicknesses, and to the number of volts required to break them down. The experiments, which were made at the Oerlikon works, consisted in putting layers of the substances between the electrodes, and gradually increasing the voltage until the substance began to heat up between the poles.

Fig. 101 relates to *micanite*, that is to say to thin laminæ of mica cemented together with a special gum such as pure shellac. It is found that when a sheet of micanite is placed between two electrodes, and the voltage is gradually raised, a point is reached when, with a sheet of given thickness, a current begins to flow through the micanite, heating it up within, and producing a burning which rapidly destroys the insulation. Micanite is a good insulator even at 150° C., and its breakdown when the limiting voltage is reached, appears to be due to the chemical decomposition, not of the mica, but of the cementing varnish. Pure mica in sheets, whether of white or of brownish or greenish tint, if clear has an enormous power of resisting puncture by the spark, some samples withstanding as much as 5000 or more volts per mil thickness. Mica-canvas consists of mica scrap sheets about 2 mils thick, overlapping one another, and cemented with shellac varnish between two sheets of canvas; the total thickness being about 50 mils and withstanding 3000 volts (alternating). Mica

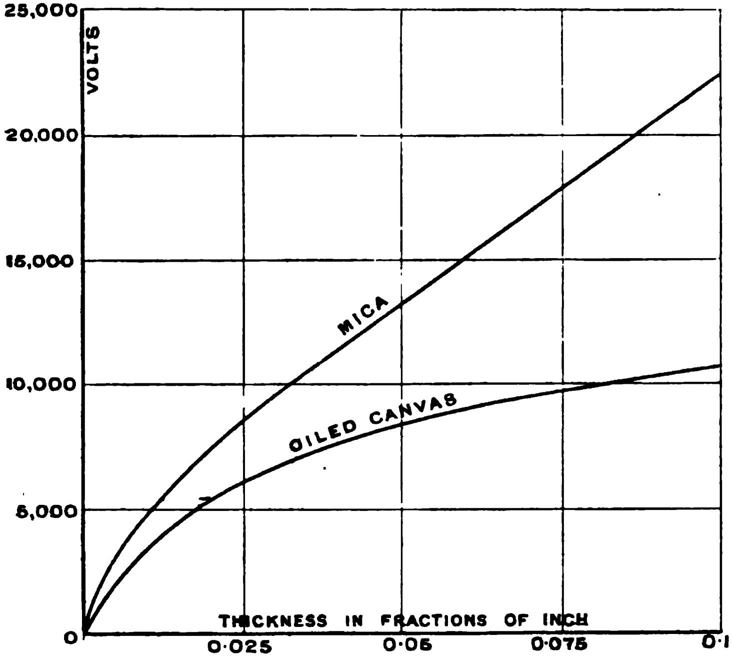


FIG. 100.—CURVES OF DIELECTRIC STRENGTH.

long-cloth consists of mica scraps similarly cemented between a very thin "linen" fabric; its thickness being about 25 mils. In making each of these compositions the sheets are baked for at least twenty-four hours in a steam-heated oven.

The data given in the following Table XII. are only very approximate, as in most cases the compositions vary somewhat, and differ at different temperatures. Taking these figures as being true at ordinary temperature of the air, it is probable that in most cases a rise of 30 deg. Centig. would reduce them to half their value, pure mica being less affected, and paraffined paper much more affected than the rest of those mentioned.

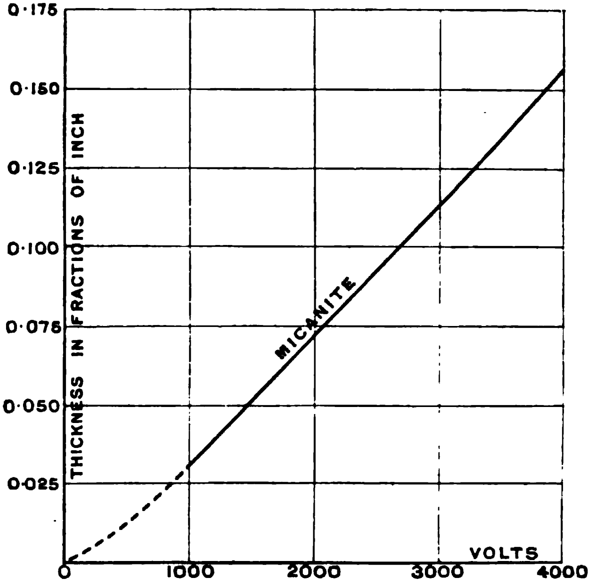


FIG. 101.—INSULATION VOLTAGE OF MICANITE.

A discrepancy appears between the figures for mica in this table (800 to 8000 volts per mil), and the Oerlikon figures (about 27 volts per mil). The Oerlikon figures relate to the production of the *heating* which indicates incipient breakdown, while the figures in the table relate to *piercing* by a sudden spark. Many makers allow, as a safe insulation, 1 millimetre per 500 volts, which is about 12 volts per mil.

Hobart using a mixed insulation allows the following thicknesses in armature slots: 1·2 mm. for 115 volt machines, 1·3 mm. for 230 volts, 1·5 mm. for 550 volts; the guaranteed insulation test from copper to iron at 20° C. being from 2500 3500 alternating volts applied for one minute.

TABLE XII.—DIELECTRIC STRENGTH OF INSULATING MATERIALS.

Material.	Dielectric Strength (volts per mil)	Megohms per mil thickness, for 1 sq. inch.	Remarks.
Mica, clear flat	800–5000	30,000	varying in quality.
Micanite plate	900–1200	1,000,000	
Mica canvas	60–70	300,000	
Mica long-cloth	60–70	300,000	
Mica paper, flexible	300–800	300,000	
Press-spahn	300–400	100	hygroscopic.
Paraffined paper	800–1000	10,000,000	softens when warm.
Oiled paper	500–900	1350	made with pure boiled linseed oil.
Shellacked paper	50–125	20	cartridge paper.
Manila paper	120	4	dried, unvarnished.
Double cotton, shellacked	250–300	25	as on D.C.C. wires.
Hard rubber	500–1200	600	varies much with quality.
Vulcanized fibre	120–200	400	hygroscopic.
Thinnest insulating tape	150	20	thickness about 7 mils.
Vulcabeston	20	15	
Dry mahogany or maple	15	0·5	
Slate	5	0·5	ought to be boiled in paraffin.

Dry wood is used in armature construction as a packing under windings to prevent abrasion where they turn through a sudden curve. Slate is only used for terminal boards, and must be free from metallic veins. Vulcabeston, consisting essentially of asbestos cemented together with a small quantity of rubber and vulcanized, is useful as being capable of being moulded: it does not lose its insulating properties if heated even to 300° C. Stabilit, which is manufactured in sheets and tubes, is said to withstand 10,000 or 15,000 volts with a thickness of 1 millimetre or about 400 to 600 volts per mil. It is non-hygroscopic and can be moulded. The measured resistance is about 40,000 ohms per mil thickness. Megohmite is a mica composition also capable of being moulded. All. paraffined compositions have a very high apparent insulation resistance, but are quite unsuitable if the temperature rises so little as 30 deg. Centigrade. Cardboard baked and then while hot impregnated with shellac or other insulating varnish makes an excellent material for lining armature slots. A preparation known as "rope-paper" when dry breaks down at about 700 volts; but when specially treated with copal varnish breaks down at from 7000 to 10,000 volts. Another paper preparation is known as "Carton Lyon." For all voltages over 500, an insulation containing mica is to be preferred, and indeed is indispensable for all high-voltage work.

There is a serious objection to resin, shellac, and to varnishes containing shellac and resin, that these substances when heated give off vegetable acids which in time corrode the copper. Hence other varnishes have been sought which are not open to this objection. Among these are "Sterling varnish" and "enamelac."

The Pittsburg Insulating Company manufactures various fabrics and papers impregnated with "Sterling varnish" and is responsible for the particulars given in Table XIII.

Sulphur mixed while melted with powdered glass, or with kieselguhr, forms a composition that can be poured into sockets or cavities and is an insulator.

Insulation of Core-Disks.—The stampings of armatures are sometimes japanned, or sometimes with sheets of thin paper placed between them. A more modern practice is to cover the thin iron sheets with paper by machine before the laminations are stamped out to shape. A coating of enamel or water-glass has also been tried. A high insulation is not needed; but it must be capable of withstanding the inevitable rise of temperature.

TABLE XIII.—PUNCTURE TESTS.

Material.	Grade.	Thickness in Mils.	Puncture Test in Volts.	Guaranteed Resistance to Puncture.
Bond paper . .	A	4– 5	5,000 – 9,000	..
Fibre paper . .	A	6– 7	8,000 – 10,000	..
Red rope paper .	A	9–10	9,000 – 11,000	..
Paper	A	6– 7	8,000 – 10,000	..
Paper	B	9–10	14,000 – 16,000	10,000 volts
Paper	C	12–14	20,000 – 25,000	15,000 ,,
Linen	A	6– 7	5,000 – 9,000	..
Linen	B	10–11	13,000 – 15,000	10,000 ,,
Linen	C	15–16	18,000 – 20,000	15,000 ,,

Insulation of Core-Bodies.—After a core-body has been assembled and properly clamped upon its spider, it must be protected by insulation, so as to diminish any risk of making short-circuit with any of the conductors. Although these are each separately insulated, insulation of the core-body is also necessary as a double protection. Smooth cores are insulated over the cylindrical surface as well as at the ends. Toothed cores are insulated along the slots, as well as at the ends. Core-bodies for ring-wound armatures must also be insulated along the inner periphery of the core. "Empire cloth" is found very suitable for covering smooth cores.

Insulation of Slots.—It is usual to line the interiors of slots with a layer of insulating material. "Empire paper" is suitable as a first lining. For machines working at 500 volts or under, a lining of varnished paper or cardboard, 20 mils thick, is considered adequate, provided the individual conductors or the groups of conductors are themselves strongly insulated with micanite of 40 mils or 50 mils thickness. Sometimes a lining of mica-paper is used. For still higher voltages, micanite linings made of sheet-micanite are used. In the case of tunnel slots, or slots that are nearly closed between T-shaped teeth, micanite tubes are preferred. These, indeed, are general in the case of high-voltage alternating generators and motors.

A good practice is to tape the conductors for all voltages to a thickness of 20 mils, and for the slot insulation to allow for 100 volts 60 mils, for 250 volts 80 mils, and for 500 volts at least 100 mils thickness, with an extra packing at the bottoms of the slots and between the upper and lower coils in the slot.

Insulation of Conductors.—Double cotton covered wires, if treated with shellac varnish, or, better, with Sterling varnish in several coats, and baked in a steam oven, are commonly used for wire-wound armatures. For armatures liable to rough usage there is preferred a treble cotton covering soaked in a special asphaltum varnish which when dry is more flexible. Former-wound coils are usually wound dry, and taped, before any coating of varnish is applied; and care ought to be taken, before any varnish is applied, to drive out all moisture. This may be done in a steam oven, or better, in a Passburg vacuum chamber, which does not necessitate so high a temperature.

For further and more detailed information the reader is referred to the following sources:—

C. P. Steinmetz.—Note on the Disruptive Strength of Dielectrics. *Trans. Amer. Inst. Elec. Engineers*, x. 85, Feb. 21, 1893.

Oerlikon Maschinen Fabrik.—Sur le Calcul de Machines électriques, June 1900.

Sever, Monell and Perry.—Effect of Temperature on Insulating Materials. *Trans. Amer. Inst. Elec. Engineers*, xiii. 225, May 20, 1895.

Baur.—On the Electric Strength of Insulating Material. *Electrician*, xlvii. 758 and 1000 (1901).

O'Gorman.—Insulation on Cables, *Journ. Inst. Elect. Engineers*, xxx. 608, March 7, 1901.

Parshall and Hobart.—Electric Generators (1900).

Canfield and Robinson.—The Disruptive Strength of Insulating Materials, *Electrical Engineer* (N.Y.), xvii. 277, March 28, 1894.

CHAPTER IX.

ACTIONS AND REACTIONS IN THE ARMATURE.

IN this chapter we deal mainly with continuous-current dynamos having armatures of either ring or drum type, and with a simple magnetic field such as is furnished by the bipolar magnet once so common in small machines of this class. Many of the considerations apply equally to the case of multipolar machines.

For the sake of clearness we will suppose the armature (as viewed from the end to which the commutator is affixed) to be rotating right-handedly; and we will further suppose that the north pole of the field-magnet is situated on the right hand, as in Figs. 114 to 116, so that the magnetic lines pass through the armature core from right to left. We shall further suppose that the coils on the armature cores are wound right-handedly. Taking this as a standard case it is afterwards very easy to see how a change in any one of these conditions will affect the induction of electromotive-force.

In Fig. 102 these points are illustrated by an end view of a ring armature. The magnetic lines proceeding from the N-pole will cross the adjacent gap-space from right to left, and enter the iron core of the armature; traversing this (as illustrated in Fig. 119, p. 215), they will then pass across the other gap-space on the left and enter the S-pole of the field-magnet. The copper wires or conductors of the armature, as each rises successively in the left-hand gap, will cut these magnetic lines. Each conductor will emerge at the top of the gap, will move over the highest part of the armature from left to right, and in descending the gap-space on the right will again cut the magnetic lines. If we now apply the rule concerning induction[1] laid down on p. 37, we shall find that the directions of the induced electromotive-forces in these rotating conductors will be as follows:—In all the conductors as they *ascend* through the left-hand gap-space, the direction of the induced electromotive-force is *toward* the observer—whilst in all those that are *descending* the other gap-space on the right the induced electromotive-forces will be directed *from* the observer. If we assume that these electromotive-forces are actually producing currents,[2] then we may say that the currents flow toward the observer in the conductors which are rising in the left gap-space; and from the observer in those that are descending the right gap-space. If the armature is wound as a ring, the currents which come in one direction in the gap-space return in the other direction down the inside of the ring. If the armature is wound as a drum, then the currents simply cross at the end of the core through connecting conductors provided for the purpose.

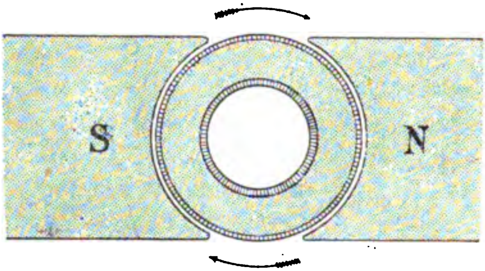


FIG. 102.—END VIEW OF RING ARMATURE BETWEEN TWO-POLE FIELD-MAGNET.

Now consider the way in which the coils on the armature are connected together. Whether wound as ring or drum they are grouped symmetrically around a symmetrical core, and united together into one closed coil; whilst at regular intervals along the windings, connecting pieces lead down to the separate bars of the commutator. Fig. 36, p. 53, shows a simple ring-winding, consisting of 32 turns of wire grouped in eight "sections" or groups, each consisting of four turns. The end of each section is joined to the beginning of the next, all the way round. There are eight bars in the commutator, and each section of the winding is connected down at its ends to two adjacent bars of the commutator. In Fig. 36 the brushes are represented as making contact respectively with the highest and lowest bars of the commutator. As the windings on the ring are right-handed, a little consideration will show, in accordance with the preceding paragraphs, that the induced currents in the ascending windings on the left-hand half of the ring will all be climbing from the lowest point to the highest; and that the currents in the right-hand half of the ring will also be climbing from the lowest point to the highest. These two currents will unite at the top bar of the commutator, and will flow together into the upper brush (which will accordingly be deemed the positive brush), and thence will go to supply the external circuit; after which the current will return to the lower, or negative brush, and will there re-enter the armature at the lowest bar of the commutator, dividing again into two parts and flowing up the two halves of the winding as before. If the conductors on the armature were wound (or connected) left-handedly, the lower brush would be the positive one, and the upper the negative. All the preceding argument would equally apply to a drum-winding (compare p. 53), but, owing to the overlapping of the two halves of the windings, the paths of the currents would not be quite so obvious.

---

[1] See footnote, p. 1.

[2] In all dynamos, when used as *generators*, the currents being set up by the electromotive-forces are of course in the *same direction* as the electromotive-forces which impel them. But it must be remembered that in the case of machines that are used as *motors* the currents are being sent in by superior electromotive-forces from outside, and that the induced electromotive-forces in the motor's armature are always in an *opposite direction* to that of the current that is flowing.

It will be noted that the current, after having entered the armature coils and divided into its two paths, goes from section to section without going down into any of the commutator bars, until both streams unite at the other side and pass down into the bar of the commutator which is for the moment passing under the brush. At those moments when one of the commutator bars is just leaving contact with a brush, and another one is coming into contact with it, the brush will rest on two adjacent bars and will momentarily short-circuit one section of the coils. While this lasts the two streams that come through the two halves of the winding will flow respectively to the two bars of the commutator, and will thus unite by both flowing into the same brush. It is obvious that if a current is introduced at any point into a closed circuit (such as the winding of a ring) and is taken out at any other point there must be two paths through the windings. In the case of multipolar machines we shall see there are usually more than two paths through the armature.

It is evident that if the magnetic lines in the gap-space are more closely crowded together in one part than in another, the electromotive-forces induced in the separate windings as they cut these magnetic lines will be of unequal amount; the greatest electromotive-force being generated in those conductors which are passing through that part of the magnetic field where the lines are crossing the gap most densely. But since the individual conductors are all united together end to end, it will be obvious that the total electromotive-force of either half of the winding, from brush to brush, will be the sum of the electromotive-forces in the separate conductors.

INDUCTION IN A UNIFORM HORIZONTAL MAGNETIC FIELD.

In considering the case of an ideal simple dynamo, it was shown that the induction in the rotating loop or coil was zero at the position where it lay across the magnetic field, and that the induction increased (as the sine of the angle) to its maximum value at about 90° (see Fig. 22, page 46). This is of course true for the ideal case of the magnetic lines going straight across horizontally with equal density everywhere. In actual dynamos the distribution of magnetic lines in the gap is different, not always symmetrical, as we shall see. Returning to the ideal case, Fig. 103, which presents a curve of *sines*, will serve to represent, by the height of the curve the amount of induction going on in an armature at every 10° round the circle. If there are, for example, thirty-six sections in a ring armature, so that the sections are spaced out at 10° apart, the least active sections will be those at 0° and 180°, while the most active are those at 90° and 270°. But in all the ordinary "closed-coil" armatures, the separate sections are connected together so that any electromotive-force induced in the first section is added on to that induced in the second, and that in the third is added to these two, and so on all the way round to the brush at the other side. The separate electromotive-forces are added together just as are the separate electromotive-forces of a battery of voltaic cells united in series. A ring of battery cells united in series, like Fig. 104, but having one-half the cells set so that the current in them tends to run the other way round the ring, forms a not inapt illustration of the induction in the sections of a ring armature.

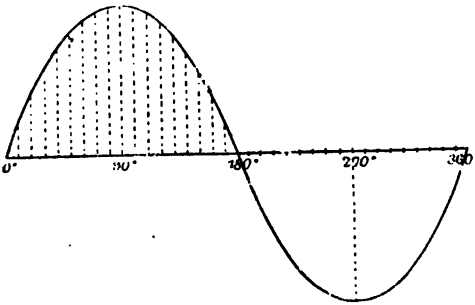


FIG. 103.—CURVE OF INDUCED ELECTROMOTIVE-FORCE.

Now, knowing how the induction in individual coils or sections rises or falls round the ring, let us inquire what this will result in when we add up the separate electromotive-forces so as to find the total effect. We shall have to add up the effects of all the sections round, from the negative brush at 0° on one side, to the positive brush at 180° on the other side: and the result will be the same in each half of the ring because of symmetry. Suppose we take the side from 0° by 90° to 180° (on the left in Figs. 22 and 102). If we look at the curve given above (Fig. 103) we shall see that as the heights of the dotted lines represent the amount of induction, the total effect will be got by adding up the lengths of all those from 0° and 180°; and of course the sum is equal to the sum of the negative lengths between 180° and 360°. But we may do the thing in another way, which, besides giving us the final total, will show us how the sum grows as each length is successively added on. We should find that the sum grew slowly at first, then rapidly, then slowly again as it neared its highest value. The sum of the effects would grow, in fact, in a fashion represented on a reduced scale in the curve of Fig. 105. This process of adding up a continuously varying set of values is called by mathematicians integrating. Fig. 105 is got by integrating the values of the curve Fig. 103 between the limits of 0° and 180°. Now in the actual dynamo this integration is effected by the nature of things, in consequence of the fact that each section is united to those on either side of it.

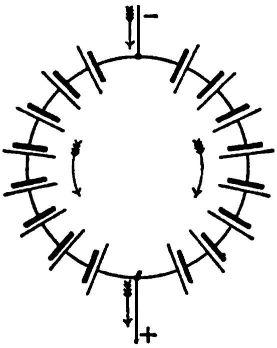


FIG. 104.

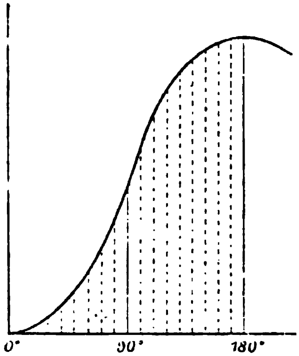


FIG. 105.—INTEGRATED CURVE OF POTENTIALS.

It is possible to investigate by experiment[1] either the induction in the individual coils or the total integrated potential. Several methods have been suggested for measuring the electromotive-forces.

---

[1] For some investigations made by the author, the reader is referred to the author's *Cantor Lectures* delivered in 1883 before the Society of Arts, and which are also described in some of the earlier editions of this book. Little depends in continuous-current dynamos on the form of these curves; but in the case of alternators the particular form of the curve of induction takes a special significance.

Use of Exploring Brushes.—The electromotive-force induced in a single section as it passes any particular position may be examined by means of a voltmeter in the following way.

S. P. Thompson's Method.—Two small metal brushes are fixed to a piece of wood at a distance apart equal to the width between two consecutive bars of the commutator. These brushes are united by wires to the voltmeter terminals. The two brushes are placed against the commutator, as shown in Fig. 106, while it rotates; and as they can be applied at any point, they will measure the average volts in that section of the armature which is passing through the particular part of the field corresponding to the position of the contacts.

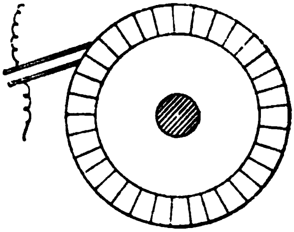


FIG. 106.—METHOD OF EXPERIMENTING AT COMMUTATOR OF DYNAMO.

Mordey's Method.—The rise of the totalized (*i.e.* integrated) potential round the armature can be measured experimentally by a method first suggested by Mr. W. M. Mordey, involving the use of a single exploring brush and a voltmeter. One terminal of the voltmeter is connected to one of the brushes of the dynamo (Fig. 107), and the other terminal is joined by a wire to a small pilot brush *b*, which can be pressed against the rotating collector at any desired part of its circumference. In a well arranged continuous-current dynamo, if one thus measures the difference of potential between the negative brush and the successive bars of the commutator one finds that the potential increases regularly all the way round the armature, in both directions, becoming a maximum at the opposite side where the positive brush is. The distribution is irregular in badly designed machines.

Swinburne's Method.—An elegant modification of the preceding method consists in connecting a high-resistance wire across the terminals of the machine, and finding by a detector galvanometer the position along this wire of the points which have the same potential as that of the pilot-brush on the commutator. Being a zero method it is very accurate.

Joubert's Method.—Another mode of examining the electromotive-force induced at every successive point in the rotation was devised by M. Joubert,[1] who placed on the shaft of the dynamo a pair of insulated metal collars connected to the ends of the armature winding; each collar having a projecting contact-piece which at each revolution made a momentary contact against a spring. The moment at which this occurred depended upon the position of the contact springs, which

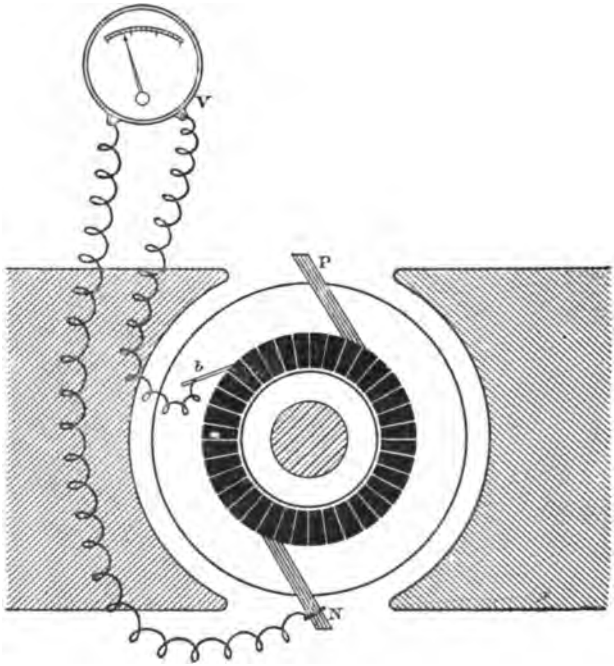


FIG. 107.—MORDEY'S METHOD OF EXPLORING THE POTENTIALS AROUND THE COMMUTATOR.

---

[1] *Annales de l'École Normale*, x. 131, 1881.

could be adjusted to different points, and thus enable measurements to be made of the instantaneous values of the electromotive-force at all different positions of the armature. Joubert's method has been extensively used, with some modifications, by many investigators for the purpose of observing the special forms of the curves of electromotive-force and of current in alternate-current machinery. The reader is referred to the chapters on alternate currents in the later part of this work.

Mordey's Statical Method.—Another method, applicable to machines at rest and without currents in the armature, consists in separately exciting the field-magnets, while the armature coils, or any one of them, are connected to a suitable ballistic galvanometer, and observing the throw caused by the sudden turning off of the current in the exciting circuit. If this is done in a number of successive positions of the armature, relatively to the field-magnet, a measure is obtained of the density of the magnetic flux, corresponding to each position of the armature, and the result may be plotted out in a curve exhibiting the distribution of magnetism in the field. This distribution is, however, perturbed, as we shall see when the machine is running by the current in the conductors of the armature.

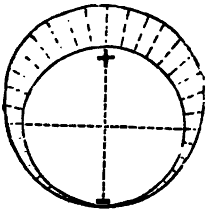


FIG. 108.—DIAGRAM OF POTENTIAL ROUND THE COMMUTATOR OF GRAMME DYNAMO.

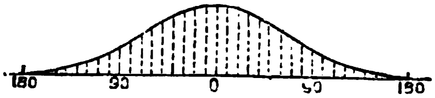


FIG. 109.—HORIZONTAL DIAGRAM OF POTENTIALS AT COMMUTATOR OF GRAMME DYNAMO.

These indications may with advantage be plotted out round a circle corresponding to the circumference of the commutator. Figs. 108 and 109 serve to show how the potential in a good Gramme machine rises gradually from its lowest to its highest value. It will be seen that, taking the negative brush as the lowest point of the circle, the potential rises perfectly regularly to a maximum at the positive brush. The same values as are plotted round the circle in Fig. 108 are also plotted out as vertical ordinates upon the level line in Fig. 109.

The steepness of the slope of the curve at different points is itself a measure of the relative idleness or activity of con-conductors in the corresponding parts of the field.

The rise of potential is not equal between each pair of bars, otherwise the curve would consist merely of two oblique straight lines, sloping right and left from the points of highest and lowest potential respectively. On the contrary, there is very little difference of potential between the commutator bars corresponding to the coils that are relatively idle. The greatest difference of potential occurs where the curve is steepest, at a position nearly 90° from the brushes, in fact, at that part of the circumference of the commutator which is in connexion with the coils that are passing through the position of best action. If the magnetic field in which the armature rotated were uniform and parallel, the curve would be a true "sinusoid," or curve of sines. The number of magnetic lines that pass through a coil would be proportional to the cosine of the angle which the normal of that coil makes with the resultant direction of the magnetic lines in the field, and the rate of cutting the magnetic lines should be proportional to the sine of this angle. Now the cosine is a maximum when the angle $= 0°$ and the sine is a maximum when the angle $= 90°$; hence the rate of increase of potential should be at its greatest when the coil is parallel to the magnetic lines.

But in ordinary dynamos with polar surfaces that embrace the armature closely on both sides (as in Fig. 102, p. 198) the field is—at least when not distorted by armature reactions—distributed nearly radially in the gap spaces; and in the parts lying between the pole-tips there are hardly any magnetic lines entering or leaving the armature. Hence in such a case the revolving conductors become active as they plunge into the gap, continue nearly equally active as they pass along the gap, and become almost idle when they emerge to pass between the pole-tips. In such a case the result of exploring the potentials by the first method will be to yield a curve such as A in Fig. 110. The corresponding curve for the total potential measured from the negative point around the commutator by the second method is indicated at B in Fig. 110.

If the brushes are badly set, or if the pole-pieces are not judiciously shaped, the rise of potential will be irregular, and there will be maxima and minima of potential, or even actual counter-electromotive forces.

As we shall see, the current in the armature reacts on the magnetic field, and distorts the distribution of magnetic lines in the gap-space.

Curves similar to those given can be obtained from the commutators of any continuous-current dynamo having a closed-coil armature. The open-coil machines used in arc lighting give widely different curves owing to the peculiar arrangements of their commutators. It should also be remembered that the presence of brushes drawing a current will alter the distribution of potential; and the manner and amount of such alteration will depend on the position of the brushes, as well as on the amount of current drawn and the design of the machine.

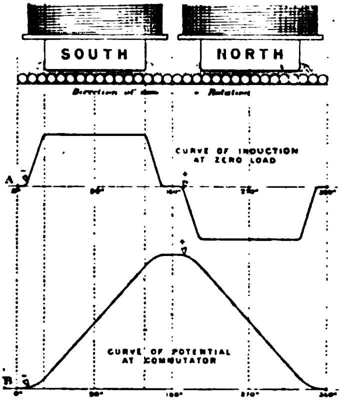


FIG. 110.—UNDISTORTED FIELD.

Curves showing the actual distortions due to the armature reaction, have been given by Von Gaisberg,[1] by Kohlrausch[2] and by M. E. Thomson,[3] also by Ryan.[4] See also a paper by Mr. Shephardson[5] on methods of exploring round the commutator.

[1] *Elektrotechnische Zeitschrift*, vii. 67, Feb. 1886.

[2] *Centralblatt für Elektrotechnik*, ix. 419, 1887.

[3] *Electrical World*, xvii. 392, 1891.

[4] *Trans. Amer. Inst. Electrical Engineers*, vii. 3, 1890.

[5] *American Electrician*, x. 453, 1898.

REACTIONS DUE TO THE CURRENTS IN THE ARMATURE.

When a dynamo is yielding a current, a set of entirely new phenomena arises in consequence of the magnetic and electric reactions set up between the armature and the field-magnets, and between the separate sections of the armature coils. The current circulating in the armature winding produces magnetizing effects which interfere with those of the exciting currents of the field-magnet. In addition to this there may also be eddy currents in the masses of metal which will perturb the magnetic field. The reactions of the running armature manifest themselves in several ways, the more important of which are (*a*) a tendency to *cross-magnetize* the armature; (*b*) a tendency to spark at the brushes; (*c*) hence the necessity of shifting the brushes through a certain angle to such a point that sparking disappears; (*d*) a consequent tendency for the armature current to *demagnetize*; (*e*) variations of sparking, and consequently of the neutral points, when the amount of current drawn from the machine is altered; (*f*) heating of armature cores and coils; (*g*) heating of the pole-pieces of the field-magnets; (*h*) a consequent discrepancy between the quantity of mechanical horse-power imparted to the shaft and the electric horse-power furnished in the electric circuit. The nature of these reactions demands careful attention.

Cross-Magnetizing Effect of Armature Current.—We have seen (pp. 201, 202, and Fig. 104) that any closed-coil armature

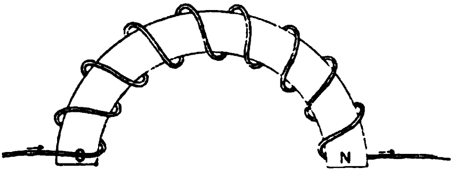


FIG. 111.—POLES ON HALF RING.

may be regarded as acting like a double voltaic battery, the two sets of coils acting like two rows of cells united in parallel.

We have now to show that a ring armature may be regarded also as a double magnet. Suppose a semi-ring of iron to be surrounded, as in Fig. 111, by a coil carrying a current, it will become, as everyone knows, a magnet having a N-pole at one end, and a S-pole at the other. If a complete ring be similarly over-wound, but with an endless winding, and if then electric currents from a battery or other source are introduced into this coil at one point, flowing round the two halves of the ring to a point at the other side, and then leave the coil by an appropriate conductor, each half of the ring will be magnetized.

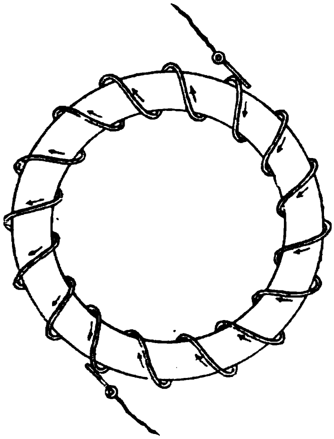


FIG. 112.—CIRCULATION OF CURRENT AROUND RING ARMATURE.

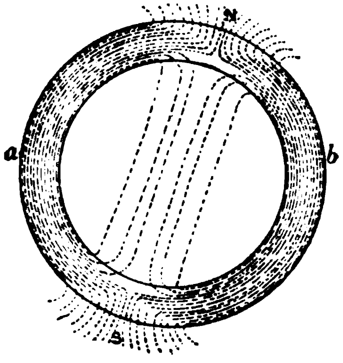


FIG. 113.—MAGNETIZATION DUE TO ARMATURE CURRENT.

There will be, if the currents circulate as represented by the arrows in Fig. 112, a double (or "consequent") S-pole at the point where the currents enter the winding, and a double N-pole at the place where the currents leave. The currents circulating in a Gramme ring will therefore tend to magnetize the ring in this fashion. Let us see how such a magnetization is distributed inside the iron itself. Fig. 113 shows the general course of the magnetic lines as they permeate through the iron; where they emerge into the air they constitute the effective poles of the ring, as a magnet. Fig. 113 should be very carefully compared with Fig. 112. It will be noticed that though the majority of the magnetic lines pass externally into the air at the outer circumference of the ring, a few of them find their way across the interior of the ring, from its N to its S-pole. This part of the magnetic field would in an actual dynamo be deleterious if the number of magnetic lines were not in reality few. The presence of the external masses of iron at the polar parts of the field-magnet tends to cause these magnetic lines to find their way externally.

It is evident that this cross-magnetizing effect will produce a distortion of the magnetic-field in the pole-pieces and in the gap-space. If, however, the brushes could be allowed to remain at the ends of a diameter exactly symmetrically between the pole-tips, the effect of the cross field upon the electromotive-force would be inappreciable. But the brushes have to be displaced into an angular position in order to avoid sparking: the diameter of commutation being oblique when the brushes are moved forward to the neutral points. When this is done the armature current produces, as we shall see, not only a cross-magnetizing effect, but also a demagnetizing effect; and this weakens the electromotive-force.

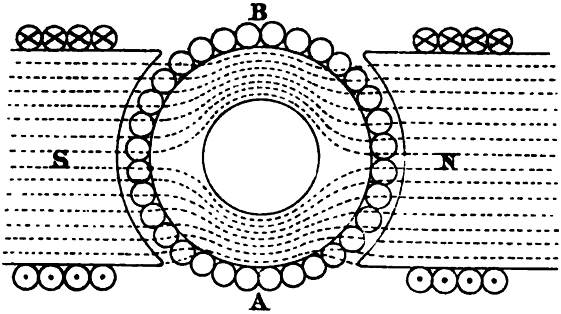


FIG. 114.—MAGNETIC FLUX THROUGH ARMATURE, WHEN NO CURRENT IS FLOWING.

Fig. 114 represents[1] the magnetic flux through an armature at rest, when the field-magnets are separately excited. The width of the gap-space is exaggerated, and the conducting wires both on the armature and on the field-magnet are shown in section as if consisting of a single layer of large round wires. Wires in which a current flows *toward* the observer are distinguished by a central dot. Wires in which a current flows *from* the observer are distinguished by a cross. The reader may think of the dot as representing the point of an arrow advancing towards him: whilst the cross may represent its retreating tail. Wires carrying no current are left blank. It will be noticed that the magnetic lines are fairly uniformly distributed both in the gap-spaces and in the polar portions of the field-magnet. The armature is drum-wound, the wires being only on the outside; the magnetizing effect of a current in it will be of the same kind as that traced out above in the case of a ring-wound armature, though less in degree.

---

[1] Figs. 114, 115, and 116 are taken, with some modification, from Esson's paper in *Journal Inst. Electrical Engineers*, xix. 135, 1890.

Suppose, now, the exciting current in the field-magnet coils to be removed, and a current sent through the armature coils only, so as to imitate the effect of the current generated by the machine when running. If it is to do this, and if the armature connexions are in right-handed order, and the machine rotating right-handedly, the currents in both sets of windings will tend to climb toward the top, the upper brush being the positive brush, and the double pole created at B will be a north pole. Suppose the brushes by which the current enters and leaves to be set respectively at the highest and lowest points, as in Fig. 115; then the dotted lines may be taken as representing the flow of magnetic lines due to the currents in the armature. Since the number of such magnetic lines depends upon the goodness of the magnetic path which they have to follow, it is clear that the cross field produced by a given current, flowing in a given set of conductors, will be greater the narrower the gap-space, and the wider the arc spanned by the polar masses of iron[1] on either side. It may also be noted that the cross-flux in either half of the armature must cross the gap-space twice.

But in an actual dynamo, when generating a current, both these magnetizing actions are going on at once. If we superpose Fig. 115 on Fig. 114, we shall obtain an approximate picture of the state of things, as Fig. 116. We supposed that

---

[1] See *Journal Inst. Electrical Engineers*, xx. 290, 1891.

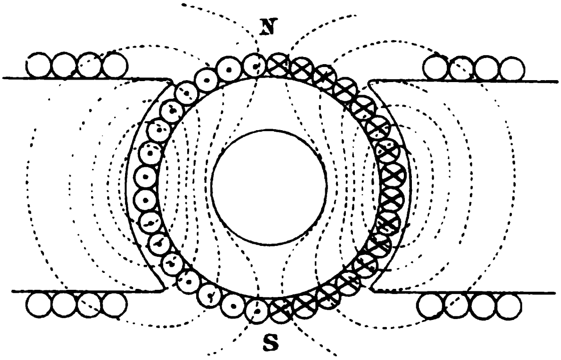


FIG. 115.—CROSS-MAGNETIZING EFFECT OF THE ARMATURE CURRENT.

the brushes were set to touch at two points on the vertical diameter. The field-magnets tend to magnetize the ring, so that its extreme left point is a N-pole, and the currents tend to magnetize it so that its highest point, where the brush is,

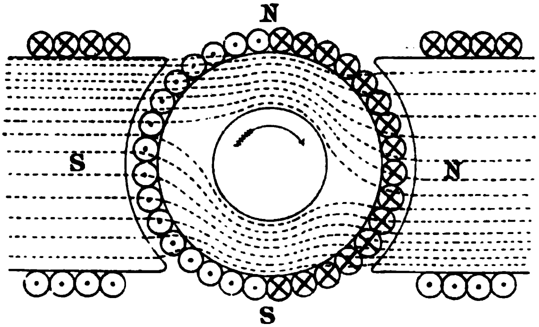


FIG. 116.—JOINT MAGNETIZING EFFECT OF CURRENTS IN FIELD-MAGNET AND ARMATURE (no lead).

is a N-pole. The consequence of this will be a resultant magnetization in an oblique direction. The magnetism is thus distorted in the direction of the rotation (in motors it is distorted the other way) as if the rotation of the armature had actually dragged the magnetism round a little. Now for reasons to be shortly discussed, the brushes must be set, not on the diameter that lies symmetrically between the pole-tips, but at an angle a little ahead of this in the direction of the rotation. Hence the cross field will also lie obliquely, tending to further distortion. Draw a line O F (Fig. 117) to represent the ampere-turns due to the field-magnet excitation, and the line O B to represent, relatively in magnitude and direction, the ampere turns due to the armature current; then the diagonal O R will represent the direction and magnitude of the resultant magnetizing tendency. This resultant we may again resolve into two components O C, a component tending to *cross-magnetize*, and O D, a component tending to *demagnetize*.

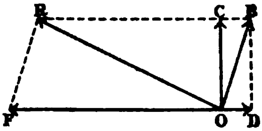


FIG. 117.

An exaggerated diagram of the distortions which result is given in Fig. 118, which relates to a ring-wound dynamo. A

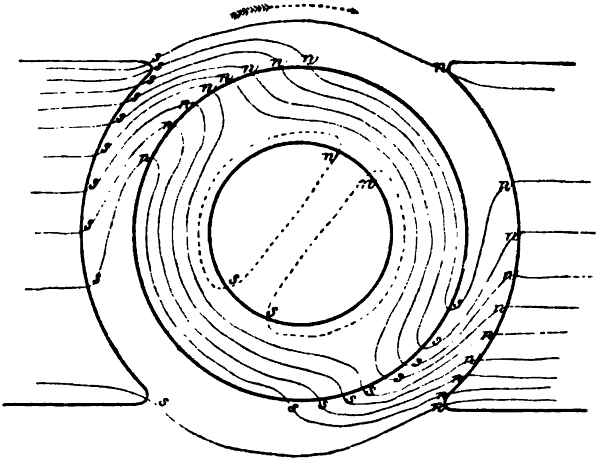


FIG. 118.—MAGNETIC REACTIONS BETWEEN FIELD-MAGNETS AND ARMATURE IN GENERATOR.

reference to Figs. 115 and 116 will also show that the magnetism of the armature reacts on the magnetism of the pole-pieces. The magnetic lines in the iron of the left pole-piece are crowded up towards the top corner, and in the right pole-piece are crowded towards the bottom, as if the polarity had been attracted upwards on one side and downwards on the other. The density of the field is completely changed from what it was in Fig. 114. The magnetic lines at the upper left side are crowded together. The resultant N-pole of the ring —marked *n, n, n,* where the lines emerge from the ring—attracts the S-pole—marked *s, s, s,* where the lines enter the field-magnet—and the steam-engine which drives the dynamo has to do hard work in dragging the armature round against these attractions. The stronger the current in the armature coils, the stronger will be the poles in the armature, and the stronger will be the attraction of *n, n, n,* toward *s, s, s*; so the steam-engine must work still harder to keep up the speed. It will also be noticed in this figure, which relates to a ring-wound machine, that a *few* of the magnetic lines due to the current in the armature—two of them are shown dotted in the figure—leak across internally and contribute nothing to the external field. The oblique direction of this internal field marks the angle of lead of the brushes. It will be remarked that the innermost layers of iron of the ring are magnetized differently from the outermost, for the "*n*" pole of the outer layer of iron occupies a region lying obliquely on the left, while the "*n*" pole of the inner layers lies to the right of the highest point. All these phenomena—the shifting of the field —its concentration under the "forward" polar horn—its weakening under the "hindward" horn—the weak internal field—the discrepancy between the positions of the induced poles on the inner and the outer sides of the ring, can be observed in an actual dynamo. Fig. 119 shows the pattern produced experimentally in iron filings by placing a magnetized ring between the poles S N of a field-magnet, which would tend to induce in it poles *n′*, *s′*, and giving its own poles *n*, *s* the proper lead. It should be compared with Figs. 116 and 118.

In the case of drum-wound armatures the phenomena, though of the same kind as with ring windings, are a little less easily traced. In consequence of the over-wrapping of the windings on the outside of the armature, the currents in some of the windings are partially neutralized in their magnetizing effect on the core by those that lie across them, and consequently the polarity due to the current is not so well marked as with ring armatures. Neither can there be any internal field. In fact drum armatures are less liable to induction troubles of all kinds than are ring armatures. But, with these exceptions, the same considerations apply to drums as to rings.

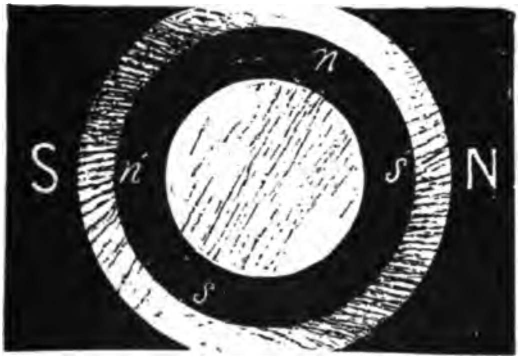


FIG. 119.—FIELD OF TWO-POLE DYNAMO.

A glance at Fig. 115 will show that as the local magnetic fields due to armature currents tend to cross each of the gap spaces twice, once in the same direction as the principal magnetic field, and once in an opposing direction, there must inevitably result a weakening of the field at that part of the gap where the revolving conductors enter, and a strengthening at that part where they are leaving, exactly as though the revolving copper swept the magnetic lines round while cutting through them. From this distortion there results a similar distortion upon the curve of induction. On exploring with pilot-brush and voltmeter, one obtains curves[1] which differ from those obtained when there is no current in the armature. Fig. 120, which shows the form of the distorted curves, should be compared with Fig. 110, p. 207.

---

[1] See also *Electric Generators* by Parshall and Hobart.

Neutral Points.—From the earliest time that dynamos have been used, engineers have found that, in order that the sparking may be a minimum, the brushes should be placed in certain positions, to be found by trial, called the *neutral points.* In ordinary two-pole dynamos the two neutral points lie at opposite ends of a diameter, which diameter is therefore called the *neutral line.* The term *diameter of commutation* ought to be reserved to denote the position actually occupied by the brushes, or by the coils that are passing the brushes, whether at the neutral point or not. Experience shows that in almost every case the neutral line is not mid-way between the pole-tips, but lies obliquely across, being (in a generator) shifted round a few degrees in the direction of rotation. It was early found that in many machines the exact position of the neutral point was different according to the work that the dynamo was doing. If the brushes were set so as not to spark when a certain number of lamps were alight, then if the load of lamps was altered the machine sparked unless the brushes were adjusted to the corresponding neutral points. Hence arose the practice of mounting the brushes on *rockers* (see Plate IV.), by means of which their line of contact could be altered forward or backward to the neutral point. Great attention has naturally been paid by constructors to the practical problem how to get rid of variations in the angle of lead.

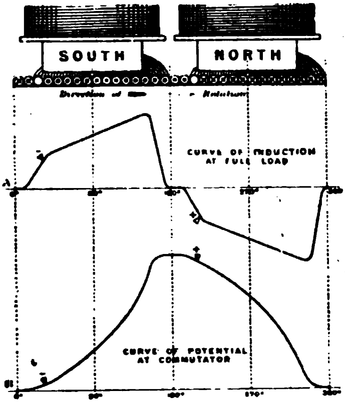

SOUTH
NORTH
Direction of Rotation
CURVE OF INDUCTION AT FULL LOAD
A
a
b
CURVE OF POTENTIAL AT COMMUTATOR
B
0°
90°
180°
270°
360°

FIG. 120.—CURVE OF ARMATURE DISTORTION.

Sparking at Commutator.—Under conditions of faulty design or adjustment, and especially when a large current is flowing through the armature of dynamo or motor, bright sparks of a blue or yellowish-green tint are observed at the commutator just under the tips of the brushes. The greenish hue is due to the volatilization of minute portions of copper. Severe sparking will spoil or destroy a commutator in a very short time. But the whole subject of *commutation* and of the sparkless collection of the current is so important that it is treated of separately in the next Chapter. Meantime it will suffice to remark that the conditions for securing sparkless commutation are vital to the subject of design, and that amongst the considerations of fundamental weight amongst those conditions are these reactions which tend to cross-magnetize and to demagnetize, which may be comprehended under the general name of armature *interference*. Important contributions to the subject of armature reaction will be found, by M. Potier, in *l'Éclairage Électrique*, vol. xix. pp. 241–246, 1899; by Mr. Bessey in the *Electrical Engineer* (N.Y.), vol. xxv. p. 511, 1898; by M. Picou, in *Bull. Soc. Internat. des Électriciens*, xvi. p. 160, 1899., and xix. p. 425, 1902; and by R. Bauch in *Elektrotechnische Zeitschrift*, xxiii. p. 611, 1902.

Dead Turns. — Owing to the various reactions which depend upon the speed, it is found that the electromotive-force of a machine excited by a given current is not strictly proportional to speed, but falls below proportionality. The machine acts as though some of its revolutions were not effective. The name *dead-turns* is given to the number of revolutions by which the actual speed at any output exceeds the number that would be needed for strict proportionality.

Spurious Resistance.—There is yet another effect which results from the existence of self-induction in the coils of the armature. In each section the current tends to go on, and in fact does actually go on for a brief time after the brush has been reached. Then the energy of the current in that section is wasted in heating the copper wire during the interval when it is short-circuited; and as it passes on, energy must again be spent in starting a current in it in the inverse direction. All these reactions are of course detrimental to the output of current by the dynamo: especially the loss in short-circuiting. It was supposed by M. Joubert[1] that the loss of energy due to the reversals of the current in the sections of a ring armature is equal to $n\,L\,C^2/4$ per second, where n is the number of revolutions per second, L the coefficient of self-induction for the entire ring, and C the armature current. Professors Ayrton and Perry very aptly pointed out[1] that the matter may be conveniently expressed in another way. Since the energy per second conveyed by a current running through a resistance r is equal to $r\,C^2$, it is evident that the energy lost per second by self-induction is the same as if there were an additional resistance in the armature of the value $r = n\,L/4$. There is, therefore, in a rotating armature, an *apparent* increase of resistance proportional to the speed, and this apparent increase, due to self-induction, cannot be got rid of by subdividing the armature into a larger number of sections. It can be diminished by using more iron in the magnetic circuit, and fewer turns of wire in the armature. The value here assigned depends on the assumption that during the moment of short-circuiting the current in the section simply dies out. If it is stopped and reversed by the introduction of a counter electromotive-force, as it ought to be, the value will be less. The existence of an apparent resistance varying with the speed was first pointed out by M. Cabanellas.[2]

---

[1] *Comptes Rendus*, June 23, 1880, January 9, 1882, March 5, 1883; and *L'Électricien*, April 1883.

Eddy-Currents.—There are two other inductive reactions in the armature to be considered. If any of the framework or metal supports that carry the armature constitute closed circuits which can cut the magnetic lines, they will be the seat of wasteful parasitic currents, which will eddy round in them, heating them and absorbing power. In the iron of the armature cores, if not properly laminated, internal *eddy-currents* (the so-called "Foucault currents") may be set up, absorbing energy and producing detrimental heat; and such currents will also be produced within the conductors which form the coil of the armature, if these are massive as in the "bar-armatures" used for machines that have a large output of current. Frölich, in 1880,[1] pointed out the effect of the presence of these currents; and to them he attributed not only the otherwise unexplained deficit in the work transmitted electrically by a generator to a motor, but also the diminution in the effective magnetism (mentioned above as a result of cross-magnetism, and found by Frölich, in the case of certain early machines, to amount to 25 per cent. of the whole) observed with great currents and high speeds. Doubtless such currents exist, and the energy they waste will be nearly proportional to the square of the speed:[2] but they may be indefinitely diminished by proper lamination, insulation, and disposition of the structures of the armature. There was much discussion about the year 1896 concerning these obscure sources of loss. Eddy-currents in the core-disks, pole-faces, and copper conductors will not, however, account for all the observed amount of energy waste. Another source is the unequal distribution of the currents between the various circuits if the poles are for any reason not equally strong. These were discussed by Messrs. Blathy, Mordey and others in the *Electrician*, vol. xxxvii. pp. 375, 420 and 446.

---

[1] *Journ. Soc. Teleg. Eng. and Electr.*, xii. No. 49, 1883.

[2] *Comptes Rendus*, January 9, 1882, and Nov. 24, 1884; see also Picou, *Manuel d'Électrométrie*, p. 123; and Lodge in *Electrician*, July 31, 1885.

Lamination.—The rules for the proper lamination of structure are different in the different parts; for in the armature core it is desired to cut off all circulation of current that might be induced parallel to the armature conductors; and in the armature conductors it is desired to cut off all flow of current from one side or edge of the conductor to the other. The plane of lamination must of course be arranged to cut right across the direction in which the parasitic current might otherwise flow. Now since (see p. 37) the direction of the induced electromotive-force, the direction of the motion, and the direction of the magnetic lines are all three at right angles to one another, it suffices in each case to describe the plane of lamination, by stating to which of these three directions it must be normal. It will then contain, or be parallel to, the other two directions.

---

[1] Berlin Academy, *Berichte*, Nov. 18, 1880; and *Elektrotechnische Zeitschrift*, i. 174, May 1881; also ix. Nov. and Dec., 1888.

[2] Clausius has introduced into his equations (*Wied. Ann.*, xx. 354, 1883; and *Phil. Mag.*, series 5, xvii. 46 and 119, 1883) terms to include the effects of the eddy-currents. They have also been theoretically treated by H. Lorberg (*Wied. Ann.*, xx. 389, 1887).

Direction of	Direction of Lamination Planes.		
	In Armature Cores.	In Armature Conductors.	In Polar Masses.
Motion	parallel	normal	parallel
Magnetic Lines	parallel	parallel	parallel
Induced Electromotive-force ..	normal	parallel	normal

It will be noticed that the lamination for the polar masses is the same as for the core; so that the polar masses are virtually continuations of the core-disks.

The necessity for dividing the cores of drum armatures and of ring armatures (if cylindrical, not discoidal) into core-disks, may be illustrated as follows:—In any conductor rising in the left-hand gap-space there will be generated an electromotive-force tending from back to front. Hence if the core were of solid iron, a current would flow forwards along the outer part of the core on the left, and back along the outer surface on the right. Division of the core into disks will obviously minimize such currents. It will not, however, entirely eliminate them, for as Fig. 121 shows in the

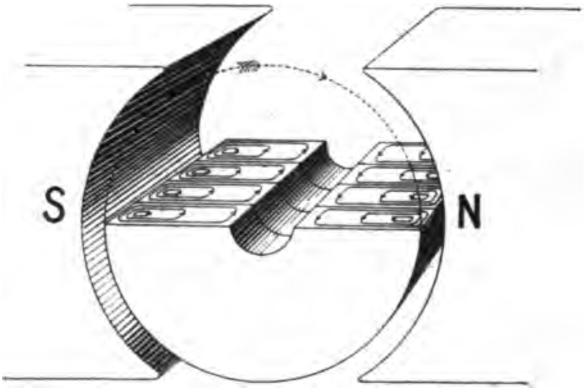


Fig. 121.—Eddy-Currents in Core-Disks.

sectional view of the core-disks, it is possible for eddy-currents to flow in the substance of these. As a matter of fact it is found that if they are too thick, or are not properly insulated from one another, they heat: and the heating is mainly at the outer surface, where the eddies are strongest. As a general rule it may be said that core-disks should not exceed 50 mils in thickness. The usual thicknesses at present in vogue are from 35 down to 16 mils. A common practice is to build up the lightly-insulated laminations of the core into blocks about an inch thick, which blocks are built up together with a thicker layer of fibre or varnished millboard interposed. If there is a stray magnetic field leaking from the flanks of the polar masses into the flat surface of the end-disks of the core, eddy-currents will also be set up in the latter. This can be obviated by making the length of the armature core rather greater than the length of the polar masses parallel to the axis.

With ring armatures that have an internal field (see p. 214) similar eddies will be set up in the driving spindle and in the metal arms that support the core, wasting power and heating them.

Eddy-Currents in Pole-Pieces.—If the masses of iron in the armature are so disposed that as it rotates, the distribution of the lines of force in the narrow field between the armature and the pole-piece is being continually altered, then, even though the total amount of magnetism of the field-magnet remains unchanged, eddy-currents will be set up in the pole-piece and will heat it. This is shown by Figs. 122 to 124, which represent the effect of a projecting tooth, such as that of a Pacinotti ring, in changing the distribution of the magnetism of the pole-piece. Figs. 125, 126 and 127 (corresponding respectively to Figs. 122, 123 and 124) show the eddy-currents, grouped in pairs of vortices. The strongest current flows between the vortices and is situated just below the projecting tooth, where the magnetism is most intense; it moves onward following the tooth. Fig. 127 shows what occurs during the final retreat of the tooth from the pole-piece. These eddy-currents penetrate into the interior of the iron, although to no great depth. Clearly the greatest amount of such eddy-currents will be generated at that part of the pole-piece where the magnetic perturbations are greatest and most sudden. A glance at Figs. 125, 126 and 127 will at once tell us that this should be at the "forward" corner or "horn" of the pole-piece of the generating dynamo. As a matter of fact, when any dynamo which has horned pole-pieces (such as the Gramme) has been running for some time as a generator this is found to be the case. The "forward" horns *a* and *c* (i. e. those which point in

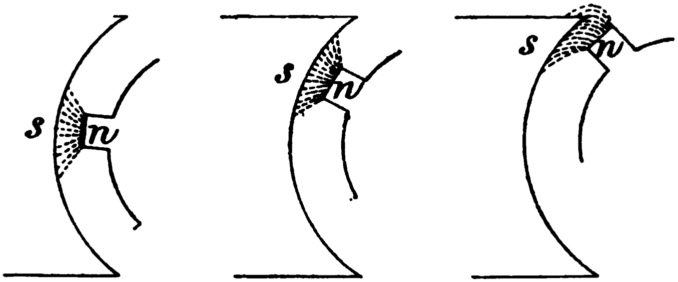


FIG. 122. FIG. 123. FIG. 124.
ALTERATION OF MAGNETIC FIELD DUE TO MOVEMENT OF MASS OF IRON IN ARMATURE.

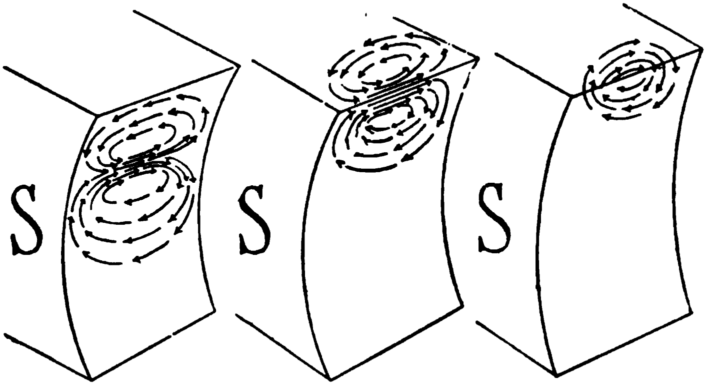


FIG. 125. FIG. 126. FIG. 127.
EDDY-CURRENTS INDUCED IN POLE-PIECES BY MOVEMENT OF MASSES OF IRON.

the direction of the rotation) are found to be hot, whilst the "hindward" horns are found to be comparatively cool. When the dynamo is used as a motor, the reverse is found to be the case: the "forward" horns are cool, the "hindward" horns are hot. A reference to the magnetic field of the motor, as described in Chap. XXV., will explain the latter case. Closely connected with this effect is another first pointed out to the author by M. Cabanellas. A Gramme magneto-machine with permanent magnets is observed to lose power during its use as a motor; the field-magnets decrease in strength. If, then, it is used as a generator, the field-magnets retain their magnetism. The effect is explicable[1] when the magnetizing effect of the eddy-currents is taken into consideration.

Drag on Armature Conductors.—Whenever a conductor carrying an electric current lies in a magnetic field across the magnetic lines, it experiences a mechanical force. This force always tends to drag the conductor sideways out of the field, and acts in a direction at right angles to the magnetic lines and at right angles to the conductor itself. Rules for remembering the relation between the directions of the magnetic lines, the current, and the resulting drag, have been given by various writers. The most convenient rule is that of Fleming (compare p. 37), in which the three directions are represented respectively by the fore-finger, the middle finger, and the thumb of the *left* hand.[2] Except in those cases where the conductors are embedded in slots or holes in the iron core-disks, the drag comes on the conductor itself. In a motor it is this drag on the conductors which drives the armature. In a dynamo the drag acts against the driving power of the steam-engine, and opposes the rotation. When a mechanical engineer first considers a dynamo he is often puzzled to understand what there is in it that necessitates so much driving power. He sees the armature revolving with ample clearance between the polar faces of the field-magnet. The friction of the bearings does not absorb more than a minute fraction of the horse-power delivered by the engine. He sees the brushes pressing against the commutator, but knows that their friction is also a negligible quantity; moreover, he is soon informed that friction has nothing to do with the operation of the machine. Where does the power go to? What is it that requires such a force to be continually exerted to keep up the rotation? The answer is, that there is a continual drag of the invisible magnetic lines on the conductors through which the current is flowing: that the generation of the current depends on the conductors being forced across the field that drags at it. In every form of apparatus generating currents by magneto-electric induction, the currents generated produce a mechanical reaction tending to stop the very motion that generates them.

---

[1] See remarks by the author at the International Conference of Electricians at Philadelphia, 1884 (reported in *Electrical Review*, Dec. 13, 1884).

[2] Contrast with p. 37, where for the current generated in a *dynamo* the *right* hand is used. Remember that in a dynamo the direction of the current agrees with that of the induced electromotive-force, whereas in a motor the current flows against the induced electromotive-force. Further, in the dynamo the mechanical drag acts against the direction of motion, whereas in a motor the drag produces the motion in the same direction as itself. Hence the use of *right* hand for dynamo, *left* hand for motor, to give the relation between magnetism, current and motion.

The drag of a magnetic field upon a conductor that carries a current may be considered from the magnetic point of view. As pointed out on p. 41, above, such a conductor is surrounded by a whirl of magnetic lines. Around a long straight conducting wire not placed in any magnetic field, these magnetic lines form a system of concentric circles (see Fig. 18, p. 41) which are close together near the conductor, and wider apart at a distance away, resembling Fig. 128 in general disposition.

If the current is coming towards the observer, or *up*, in the figure which shows a cross-section of the conductor, the positive direction along the magnetic lines will be counter-clock-wise. If now such a conductor be placed in a uniform magnetic field—one, for example, between a large north magnetic pole on the right and a south magnetic pole on the left, a compound field will be produced, due to the blending of the magnetic lines of the current with those of the field. In considering this distorted magnetic field it should be remembered that the mechanical actions that result may always be known by supposing the magnetic lines to act as elastic cords tending to shorten themselves. There is in fact a tension along the magnetic lines and a pressure at right angles to them, both proportional at every point to the square of their density. A mere inspection of the lines of Fig. 129 will accordingly show that there will be a resultant drag upon the conductor in the direction shown by the dotted arrow.

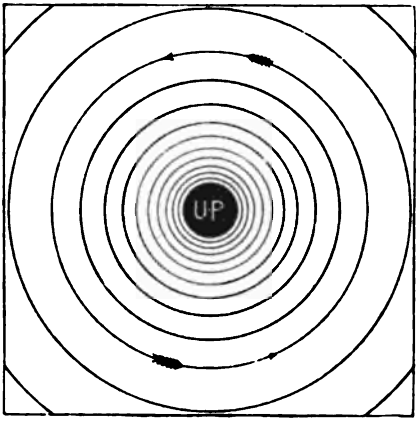


Fig. 128.—Magnetic Field of a Straight Conductor Carrying a Current.

The actual magnetic field produced around a conducting wire in a gap between two poles, as revealed by iron filings, is shown in Fig. 130. We may consider this as approximately representing that which goes on in a dynamo, or in a motor, in each of the gap-spaces between the armature core and the adjacent polar face. Each conductor in the gap will be similarly dragged by a force proportional to the

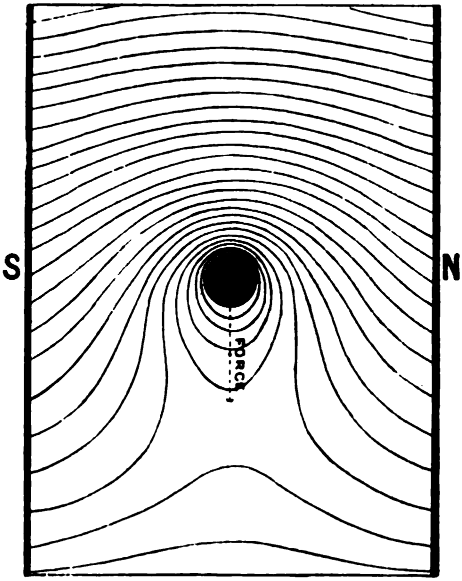


Fig. 129.—Magnetic Lines due to Conductor Carrying Current placed in Magnetic Field.

intensity of the magnetic field and to the strength of the current.

Effect of Embedding Armature Conductors.—If the conductors are embedded in slots or holes in the core-disks (see Figs. 131 and 279) the drag then comes not upon the copper conductors, but upon the iron; the magnetic field between the core-disk and the pole-faces being distorted by the current in the embedded conductors. In fact the conductor no longer lies in a strong magnetic field; the magnetic lines being carried past it on either side, very few going through it.

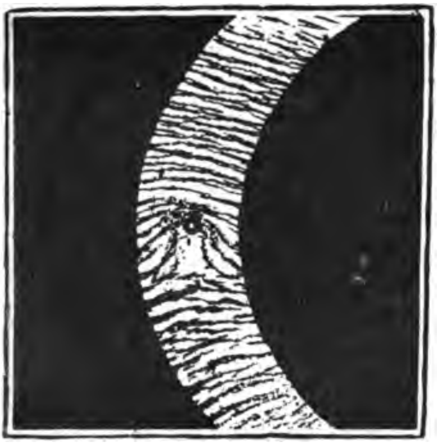


FIG. 130.—ACTUAL MAGNETIC FIELD AROUND CONDUCTING WIRE IN MAGNETIC GAP.

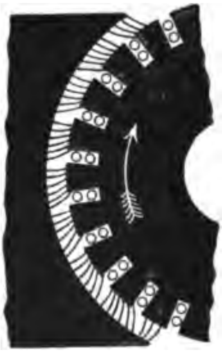


FIG. 131.—MAGNETIC FIELD OF SLOTTED ARMATURE.

Fig. 131 may assist the understanding of this point. It seems paradoxical that though the conductor so embedded is protected from mechanical drag, and from eddy-currents, owing to its not being in the field, nevertheless in its revolution it still cuts all the magnetic lines precisely as if it were not protected. The effect is as though the magnetic lines flashed across the slots from tooth to tooth, instead of passing across the intermediate slot at the ordinary angular velocity. In addition to the advantages already mentioned as possessed by these forms of construction, they have also the very important one of reducing the breadth of the magnetic gap to a mere clearance. Some experiments on the drag on embedded conductors, by Mr. Mordey, are described in *Journ. Inst. Electr. Engineers,* xxvi. p. 564. 1897. For a further discussion of the mechanical stresses in slotted armatures see a paper by Mr. P. M. Heldt in the *Electrical World and Engineer,* vol. xxxiii. p. 699, 1899.

Torque and Speed.—Engineers recognize that power, being the rate of doing work, can always be expressed as the product of two factors. In the case of rectilinear motion, the power may be expressed as the product of force and speed. For example, if the force pulling along a belt[1] be equal to the weight of 66 lb., and the belt-speed be 2000 feet per minute, the amount of power it is delivering is 132,000 foot-pounds per minute, or 4 horse-power.

But the power may be equally well expressed in terms of angular force (*i.e.* torque) and angular speed; and these quantities are more convenient in the case of power transmitted along a rotating shaft.

The useful term *torque*, now generally accepted by engineers, was originally suggested by the late Professor James Thomson. It is the same thing as that which has gone by the names of "turning moment," "moment of couple," "axial couple," "angular force," "axial force," in German by that of "Zugkraft," and in French by those of "effort statique," and "couple mécanique." *Torque* is preferable in many ways to any of the older terms. Just as the Newtonian definition of *force* is that which produces or tends to produce motion (along a line), so *torque* may be defined as that which produces or tends to produces *torsion* (around an axis). It is better to use a term which treats this action as a single definite entity than to use terms like "couple" and "moment," which suggest more complex ideas. The single notion of a twist applied to turn a shaft is better than the more complex notion of applying a linear force (or pair of forces) with a certain leverage.

For torque we shall use the symbol T. If force f acts with leverage (*i.e.* radius) r, the torque is equal to $f \times r$. If the force is in pounds' weight and radius in feet, the torque will be expressed in pound-feet; *i.e.* in terms of the number of pounds which, acting with a leverage of one foot, would produce an equal tendency to turn. If force is given in dynes and radius in centimetres, the torque will be expressed in dyne-centimetres.

---

[1] Or more precisely, the difference between the forces in the tight and slack parts.

In order to bring—

dyne-centimetres	to	gramme-centimetres,	divide by 981
dyne-centimetres	to	metre-kilogrammes,	divide by 981×10^5
dyne-centimetres	to	pound-feet,	divide by $13 \cdot 59 \times 10^6$
pound-feet	to	metre-kilogrammes,	divide by 7·23

Angular speed is commonly expressed by engineers in terms of the number of revolutions per minute, or, sometimes of revolutions per second. The scientific mode is to express it in *radians per second.* (The radian is that angle whose arc equals the radius; so that 2π radians equal one revolution or 360°). The symbol for angular speed is ω, so that if n represents the revolutions per second, $\omega = 2\pi n$.

In order to bring—

revolutions per minute	to	revolutions per second,	divide by 60
revolutions per second	to	radians per second,	divide by 2π
revolutions per minute	to	radians per second,	divide by 9·55
radians per second	to	revolutions per minute	multiply by 9·55

We have then the following relations between linear force f, linear speed v, torque T, angular velocity ω, radius r, revolutions per second n, and power w.

$$w = v . f = \frac{v}{r} . fr = \omega \mathrm{T} = 2 \pi n \mathrm{T}.$$

The power w will be expressed in *ergs per second,* if v is given in centimetres per second and f in dynes; or if T is given in dyne-centimetres. If T is in pound-feet, w will be expressed in foot-pounds per second.

In order tô bring—

ergs per second	to	watts,	divide by 10^7
ergs per second	to	kilogramme metres per second,	divide by 9·81 × 10^7
ergs per second	to	foot-pounds per second,	divide by 1·356 × 10^7
ergs per second	to	horse-power,	divide by 746 × 10^7
watts	to	horse-power,	divide by 746
watts	to	chevaux-vapeur,	divide by 736
watts	to	foot-pounds per second	divide by 1·356
watts	to	kilowatts,	divide by 1000
kilowatts	to	horse-power,	multiply by 1·345

Output of Dynamos and Motors.—A good dynamo will convert over 90 per cent. of the mechanical power supplied to it into electric power. Similarly a good motor will convert over 90 per cent. of the electric power supplied to it into mechanical power. Both mechanical power and electric power may be expressed in terms of the same units, either in *horse-power* or in *watts*, or in *kilowatts.*

Approximate calculations of the horse-power required for a dynamo of any prescribed output are readily made. Multiplying the number of amperes C of current which the dynamo is to yield, by the number of volts V of pressure at which the current is supplied, gives the output in *watts.* Dividing by 746 gives the corresponding electric horse-power, which will be about 90 per cent. of the mechanical horse-power to be supplied to the shaft of the dynamo.

Example: A dynamo is required to furnish 300 amperes (to light 600 glow lamps) at a pressure of 105 volts. Output is 31,500 watts = 42·2 horse-power (electrical). Therefore allow 46·9, or say 50 (mechanical) horse-power.

In the converse way we may calculate the requisite supply of electric power to a motor.

Example: A motor is required to give an actual output of 5 horse-power. Multiplying by 746, we find it must give out 3730 watts as mechanical power; which will be about 90 per cent. of the electrical power supplied to it. This will therefore need to be about 4144 watts. If the supply is from mains that are at a pressure of 200 volts, the current required will consequently be a little over 21 amperes.

Relation between Torque and Current.—Since the electric power given out by the armature of a dynamo is the product of two factors—volts and amperes—and the mechanical power supplied to it by the rotating shaft is also the product of two factors—speed and torque—it becomes a matter of some interest to ascertain whether there is any direct relation between the factors themselves. Let E stand for the volts generated in the armature, and C_a for the amperes flowing through it. We may then equate the two separate expressions for the number of watts of power supplied to and furnished by that armature as follows:—

$$\text{watts} = E\,C_a \times 2\pi n T \times 1\cdot356;$$

where T is given in pound-feet; n in revolutions per second; E the whole volts generated by the armature; and C = whole amperes flowing through the armature. But E is proportional to the speed if the magnetism is constant, the fundamental expression for it being (see pp. 281 and 282) for an ordinary ring-wound or lap-wound machine,

$$E = n\,Z\,N \div 10^8;$$

where Z is the number of conductors around the armature, and N the magnetic flux entering from one pole. Inserting this value for E, and cancelling n from both sides, we get:

$$\frac{Z\,N\,C}{1\cdot356 \times 10^8} = 2\pi T;$$

whence

$$T\ (\text{in pound-feet})^1 = \frac{Z\,N\,C_a}{8\cdot52 \times 10^8};$$

which may also be written:

$$T\ (\text{in pound-feet}) = 0\cdot1175\,C_a\,Z\,N \div 10^8. \quad [1]$$

From this it appears that if in a given machine the magnetism is constant, the torque depends in no wise upon the speed, but only upon the current flowing through the armature, and on the magnetism. If, for brevity, we write $M = Z N \div 10^8$, the formula becomes

---

[1] If T is desired in metre-kilogrammes, the divisor on the left must be replaced by the value $61\cdot5 \times 10^8$.

$$T \text{ (in pound-feet)} = 0{\cdot}1175\, C_a M, \quad . \quad . \quad [2]$$

which is the fundamental formula for all motor work.

These expressions apply equally to dynamos and to motors. They show that if it is desired to build slow-speed machines provision must be made for a very large magnetic flux; for only by making the product of Z and N large can the dynamo at slow speed yield the requisite volts, or the motor exert the needful torque.

A number of curves, called *mechanical characteristics*, giving the relations between speed and torque in a number of different cases, will be found in Chapter XXV.

Drag on Armature Conductors.—We are now in a position to understand the drag on the armature. Setting aside for the moment the case of embedded conductors, we may at once proceed to calculate the amount of such drag. There are three methods of doing this: two being electrical and one a purely mechanical calculation.

METHOD I.—By the last formula the torque is calculated; and from this the total peripheral force is found by dividing by the known radius of the armature. Hence the force per conductor is obtained by dividing the number of active conductors.

Example in the Edison-Hopkinson dynamo (Fig. 12), $C_a = 326$; $Z = 80$; $N = 10{,}850{,}000$; radius $= 0{\cdot}458$ feet; whence $T = 332$ pound-feet, and total peripheral force $= 724{\cdot}7$ lb. This would give about 9 lb. average force per conductor if all were active; but only about 58 of them are in the magnetic field at one time; hence, the average force per conductor is about $22\frac{1}{2}$ lb. If the magnetic field in the gap-spaces is not uniform there comes a stronger drag on those conductors which lie in the densest field.

METHOD II.—The drag on a conductor of length l, in a magnetic field of intensity H, carrying current of C amperes, is

$$f \text{ (dynes)} = C\, l\, H \div 10. \quad . \quad . \quad . \quad [3]$$

This formula[1] is only applicable if H, the density of the field in the gap-space, is known. If l'' and $H_{''}$ are given in inch measures (see p. 78), the formula becomes

$$f \text{ (lbs.)} = C\, l''\, H_{''} \div 11{,}303{,}000. \quad . \quad . \quad [4]$$

Example, as before: Current in any one conductor will be $\frac{1}{2}C_a$ = 163 amperes; l'' = 20″, and $H_{''}$ = about 43,300 lines per square inch, the area of the gap-space being about 250 square inches. Whence drag on each conductor = 12·49 lbs.

METHOD III.—Ascertain actual horse-power on armature; multiply by 33,000 to reduce to foot-pounds per minute, and divide by the peripheral speed (in feet per minute). [The horse-power may be reckoned from the electrical output as on p. 229.] Then divide by the number of active conductors. Or, in symbols,

$$f \text{ (lbs. average drag per conductor)} = \frac{\text{H.P.} \times 33{,}000}{\text{ft. per min.} \times Z}.$$

Example, same as before: Since i_a = 326, and E = 108·5 volts, H.P. = 326 × 108·5 ÷ 746 = 47·45. Also periphery = 2π = radius = 288 feet. This, at 750 revs. per minute, gives 2158 feet per minute as peripheral speed. Assuming fifty-eight conductors to be active, we get

$$\text{av. force on each conductor} = \frac{47{\cdot}45 \times 33{,}000}{2158 \times 58} = 12{\cdot}5 \text{ pounds.}$$

A convenient approximate rule may be given as follows:—If we assume, as a sort of rough average for the magnetic-field in the gap-space of a dynamo or motor, the value of 40,000 lines to the square inch, or say 6300 lines per square centimetre, then *the drag per inch of conductor will be* 0·00354 *pound for each ampere of current carried.* In alternate-current dynamos the intensity of the field is seldom as great as this.

Such, then, is the drag that magnetic fields exert upon non-embedded armature conductors; and, it must be remembered that the drag is not a steady one. When the conductor emerges from the gap-space, though there is still a current in it, the magnetic drag is taken off. Twice, therefore, in each revolution this drag is suddenly removed and suddenly put on again, increasing the raking action. In the case of alternate-current machines, where the relation of phase between the currents and the magnetic fields complicates the matter, the drag is not simply taken off and put on twice in each complete period, but is actually reversed; the armature conductors being driven with a back drag on them, then experience a forward drag and tend to drive, then once more are driven, and again tend to drive as the current reverses. In the alternate current machine acting as generator the intermediate forward drags are slight and of short duration; in the machine acting as motor it is the backward drags that are of short duration.

---

[1] To give f in kilogrammes, the divisor 10 must be replaced by 9,810,000.

If the conductors are sunk in slots, the drag, as pointed out on p. 226, comes upon the iron teeth instead of the copper; unless, indeed, the teeth are very highly saturated magnetically, in which case there will be a measurable drag also on the copper conductors.

Need of Driving Horns.—It is then obvious that under the mechanical conditions now described, if the conductors are not embedded in slots between teeth on the core-disks there is need of a good positive method of conveying the driving power to them from the shaft. In the dynamo it is they that need to be driven. In the motor, it is they that drive the shaft. The question of construction is complicated by the consideration that whilst the copper conductors must be mechanically connected to the shaft in the most positive way, they must not be metallically connected, but on the contrary, must be insulated therefrom. Different constructors adopt different modes of accomplishing the end in view. Compare the practical modes adopted by modern makers described in Chapter XIV.

Stray Power.—In the preceding paragraphs it has been assumed that the mechanical power applied *at the shaft* to drive the armature was equal to the electrical power actually generated in the armature. The power to be applied at the pulley is, however, always greater than this ; for, in the first place, some of the applied power is lost by friction in the bearings, &c., and never reaches the armature. But of that which actually reaches the armature, not all is actually converted into electrical power. There are, beside the friction at the bearings and brushes, three sources of loss, viz.: (1) air-friction, (2) hysteresis, (3) eddy-currents. The first of these is insignificant, except in those cases where curved spokes are employed with the object of making the armature act as a fan, and even then is small. The second is by no means negligible, but seldom adds more than 1 or 2 per cent. to the driving power. The third is the most important of all, especially in large machines. In all the moving metal masses, unless laminated, there will be eddy-currents set up if they cut magnetic lines. Even in the metal of the shaft power may be lost from this cause if there is leakage of magnetic lines into it. The mode of investigating the separate sources of loss is described in Chapter XXVII., on the Testing of Dynamos and Motors. Whatever these losses, it is evident that they all call upon the supply of power: for the power supplied is necessarily equal to the sum of the power actually converted in the armature into electric power, and the stray power wasted in the ways enumerated.

Need of Powerful Field-Magnets.—It has been stated on p. 230, that the output of a machine at a given speed is proportional to the product of Z and N. But, for a given current, the reaction of the armature that gives rise to spark-troubles is proportional to Z. To keep down armature-reactions it is then advisable that Z should be kept small, and therefore it follows that N must be kept large. In other words, the machine must be designed to have large and strongly magnetized field-magnets.

CHAPTER X.

COMMUTATION ; CONDITIONS OF SUPPRESSION OF SPARKING.

SINCE, as we have seen, the movement of the armature coils past the magnet poles necessarily generates alternating currents, the *commutator*, which will commute these into one direction, becomes a necessary part of all continuous-current machines. The act of commutation needs very special study. If it is incorrectly performed by any continuous-current machine, whether generator, motor, or converter, the imperfection at once makes itself shown by the sparks which appear between the commutator and the brushes. This sparking is intimately connected with the various reactions of the armature, and must be discussed thoroughly.

Cause of Sparking.—The sparks which appear at the commutator under conditions of faulty design or adjustment are observed just under the tips of the brushes. If a new commutator, or one that has recently had its surface renewed in the lathe, be examined after sparking has taken place, it will be noticed that the edges of many or all of the commutator segments will appear as if burned. But the burnt appearance will always be—no matter whether in generator or motor—at the edge of the segment which was the last to touch the brush ; the advancing edge in the direction of the rotation will not show signs of burning. This proves that the spark that produces the damage occurs just as the copper segment, after passing under the brush, parts from contact with it. The *cause* of sparking is not difficult to show. All the conductors in the armature have their currents reversed and re-reversed at every revolution. In bipolar machines the reversal occurs twice in each revolution. In multipolar machines more than twice. In the case illustrated in Fig. 116

the current flows toward the spectator in all the conductors as they rise on the left side, but flows from the spectator in them as they descend on the right. Reversal occurs at the moment when the conductor, or the section of which it forms part, passes the brush or undergoes commutation. The production or non-production of sparks depends on the conditions under which the commutation or reversal of current takes place, and is a consequence of the property of *self-induction*—the property in virtue of which (owing to the current in a conductor setting up a magnetic field of its own in the surrounding space) it is impossible instantaneously to start, stop, or reverse a current.

The Act of Commutation.—Consider the standard case of a ring armature construction in sections, each section consisting of one or two turns of conductor. The currents will be reversed successively in the separate sections, one section at a time, as they come up to the neutral points ; or rather two at a time if commutation goes on simultaneously at each of the brushes. Half the currents flows up the coils on the left-hand half of the ring, and the other half of the current flows up the coils on the right-hand half. If the positive brush is at or near the top, as in Fig. 132, the current flows from left to right through the sections X and W on the left of the brush, and from right to left through the sections T and U on the right of the brush. Now as the armature turns the bars of the commutator come successively into contact with the brush. In Fig. 132 the bars *c* and *d* have already passed the brush ; *e* is just leaving it, and *f* is just beginning to pass under it. For a brief moment the brush rests on two adjacent bars *e* and *f*, and thus short-circuits the section V for an instant. The duration will obviously depend on the speed of rotation, on the breadth of the insulating film between the commutator bars, and on the breadth of the contact surface of the brush. Now the section V a moment previously belonged to the left-hand half of the ring, and when it has passed the brush, that is to say, when *e* ceases to touch the brush, it will belong to the right-hand half of the ring. It is clear then that in the act of passing the brush the current that was flowing in the section V will be stopped, and then started again in the opposite direction through its coils. Every section of the armature as it passes the brush will similarly be transferred from one half of the ring to the other, and will have its current reversed. This is in fact *the act of commutation.* Now suppose it were arranged that the act of commutation should occur exactly at the point when the coils of the section are not cutting any magnetic lines whatsoever: so that while the coil is short-circuited it

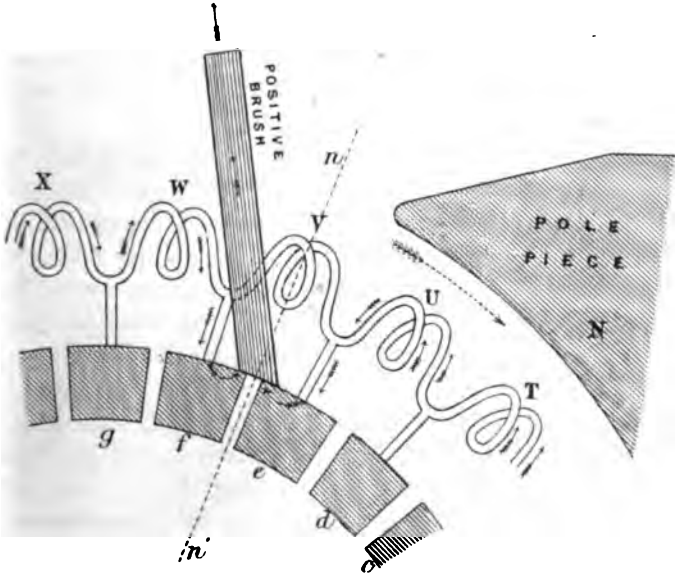


Fig. 132.—The Act of Commutation of a Section of the Armature of a Generator.

shall not be the seat of any induced electromotive-force. Then the current in it will die out, and as it emerges from under the brush it will be thrown as a perfectly idle coil upon the right-hand half of the ring, in which a current is flowing toward the brush. Just before the bar *e* parts company from the brush, the current coming up through T and U is flowing through *e* to the brush: but as *e* moves away this current has suddenly to go also round the coils of V. But because of self-induction the current cannot instantly rise to its full strength in the idle coil V, hence before V really gets to work, the current sparks across between *e* and the brush.

Theory of the Reversing Field.—We have here supposed V to be a perfectly idle coil : now suppose that it is not idle but is actually still cutting magnetic lines, as would be the case if the brush, instead of being shifted forward to the neutral line *n n'*, had been given a *backward* lead further to the left. Then it is clear that during the moment of short-circuiting there will be an electromotive-force acting in the coil as it passes the brush. Such an electromotive-force, even though small, may produce momentarily a large current, because the short-circuited resistance is so small. Hence the sparking will be worse than if the coil was absolutely idle.

Now suppose that the brush is shifted just so far the other way, in the direction of the rotation,[1] that as the coil passes the brush it is beginning to enter the fringe of the magnetic field on the right. In that case it will be beginning to cut the magnetic lines in such a way as to tend to set up a current in the reverse direction through it. The ideal arrangement is attained if the brushes be shifted just so far beyond the point of maximum electromotive-force that while the sections pass under the brush and are short-circuited they should actually have a small reverse electromotive-force induced in them ; and this action should last just so long in each successive section as to stop the current that was circulating, start a current in an opposite direction, and let it grow exactly equal in strength to that which is circulating in the other half of the armature, which it is then ready to join. If this set of conditions could be attained there should be *no sparks.* A magnetic field of the proper intensity to cause reversal in the commutating section of the winding can usually be found just outside the tip of the pole-piece, for here the fringe of magnetic lines presents a density which increases very rapidly. Since a more intense field is needed to reverse large currents than is required for small ones, it follows that the angle of lead that must be given to the brushes will be slightly greater for large currents than for small ones. Time must be allowed for reversal, hence the brushes must not be so thin as merely to bridge the width of the insulation. Sparking can indeed sometimes be cured by merely using thicker brushes which prolong the time during which the section is short-circuited.

---

[1] In the case of a motor, which is separately considered in Chap. XXV., the brushes must be shifted in the *opposite* direction to the rotation ; *i. e.* there must be a negative lead.

If the brushes are too thin, or are not rocked sufficiently far forward, there will be free sparking. If they are shifted beyond the neutral points, the sparking is in general less. That is to say there is usually much sparking when the lead is too little; a little sparking when the lead is too great; and no sparking when the lead is right. When the lead is greater than is necessary there is a waste of energy due to the generation in the short-circuited coil of a larger reverse current than is necessary. Moreover, as the lead is increased beyond the neutral point, all the coils that lie in the region between the neutral point and the diameter of commutation are exerting counter-electromotive forces, and the potential of the brushes falls from its maximum.

Commuting with Brushes in a fixed position.—The explanation given above as to what happens during commutation must only be regarded as the broad idea. Modern machines, both generators and motors, are invariably operated sparklessly at all loads with *fixed* brushes, these being set at the average load. Now we have seen that the condition for sparkless running is that the current in the short-circuited coil must be reversed, that is, reduced to zero, and then increased in the opposite direction up to the same value as it had prior to the coil being short-circuited. We saw that this condition was attained by performing the commutating operation in a suitable reversing field whose value depends upon the amount of the current to be commuted. But obviously, if the brushes are to remain in a fixed position, this condition will only be realised at the particular load for which the brushes are set. For example, let us suppose that such a position was found for the brushes that the machine ran quite sparklessly at three-quarter load. At one-quarter load, a smaller reversing field is required properly to commute the current in the short-circuited coils, and consequently there will be an excess of reversing electromotive-force over that required to reverse and build up the current again unless the brushes are shifted back so that commutation may be performed in a weaker field. In the same way, at full or overload, we require a stronger reversing electromotive-force to commute the current, which certainly cannot be provided by the reversing field available, and which is moreover less than before on account of increased distortion. Briefly then, we see that with the brushes set in an average position, the reversing field is correct for the load corresponding to this position, but wrong for every other load, being stronger when it should be weaker and *vice versa.* It becomes clear then that in order to explain what happens during sparkless (or practically sparkless) collection, with fixed brushes, some other factor has to be considered. This factor is simply the difference of potential due to the varying contact-resistance of the brushes.

Theory of Contact-Resistance.—The theory of the reversing magnetic field laid down above is, however, inadequate to explain how it is possible in certain cases to commute sparklessly without giving to the brushes any angular lead at all, in which case the coils at the instant of commutation are not passing through any reversing field. This is the case of tramway motors having the brushes set precisely at the neutral points, so that the armature may run either forward or backward. The necessary conditions for commuting without lead and without a reversing field are (1) that *carbon brushes* are used, giving an adequate contact-resistance, (2) that sufficient *time* be given to the act of commutation, or in other words, that the breadth of the brushes be sufficiently great, covering two, three, or even four segments of the commutator.

It is needful to refer here to such data as exist respecting the contact resistance offered by brushes, and its dependence upon the current-density at the surface of contact.

Carbon brushes are in practice worked at current-densities of about 40 amperes per square inch for machines of medium and large outputs. For small machines this figure may be considerably exceeded, but the maximum permissible figure is 80 amperes per square inch. Copper brushes are generally worked at 150 to 200 amperes per square inch, or even more.

Recent tests made by Professor Arnold[1] upon commutator losses show that both for carbon and copper brushes, the contact resistance decreases rapidly with increasing current-density relatively to the peripheral speeds, it being more marked in the case of carbon. According to his experiments the contact resistance of carbon brushes for current-densities of 50 to 30 amperes per square inch and peripheral speeds of 1200 to 2400 feet per minute may be taken as being 0·023 to 0·039 ohm per square inch of contact. For copper brushes the corresponding values may be taken as being 0·00077 to 0·0023 ohm per square inch. So that we can safely assume as outside values of the contact resistance per square inch :

For carbon brushes . .	0·04 ohm.
„ copper „ . .	0·003 ohm.

These values enabling us to easily calculate the commutator loss brought about by contact resistance for any machine.

Example.—In a large electro-metallurgical dynamo by Brown with an output of 4000 amperes, there are about 160 square inches of brush contact surface, or 80 square inches for entry and 80 for exit of the current, collecting about 50 amperes per square inch. Assuming the contact resistance at 0·02 ohm per square inch we find the whole C^2R loss will be

$$2 \times 4000 \times 4000 \times \frac{0·02}{80} = 8000 \text{ watts.}$$

Under the positive brush, that is, where the current flows from copper to carbon, the contact resistance is somewhat greater than that under the negative brush, where the flow is from carbon to copper. This possibly explains the circumstance that at an overload the negative brushes generally show sparks before the positive ones.

---

[1] See *Elektrotechnische Zeitschrift*, No. 1, 1899. See also Dr. Max Kahn, *Der Uebergangswiderstand von Kohlenbürsten* (Stuttgart, 1902), and Moore's results in Parshall and Hobart's *Electric Generators* (London, 1900), p. 271.

The contact resistance is not constant, but varies approximately inversely as the current density; thus, with 1·5 lb. per square inch pressure the resistance is about 0·04 when the current density is 20 amperes to the square inch, and goes down to about 0·02 when the density is 40 amperes to the square inch. Hence it follows, that the drop of potential due to this contact resistance is nearly constant at all loads, and may be taken at from 0·8 to 1·0 volt at each side, positive and negative, of the commutator, or from 1·6 to 2 volts on the whole machine.

Let us take the case considered above of a machine running with its brushes so adjusted that there is no sparking at three-quarter load, and consider in detail what happens at loads above and below this.

I. Above three-quarter load. Here, as we have seen, the reversing field is not strong enough of itself to reverse the current in the short-circuited coil. Referring to Fig. 132 we see that the coils coming from the left-hand side of the armature come under the brush with a current in them which must first be reduced to zero, and then built up again to its original value, attaining this just as it leaves the brush. Consider first what happens with the segment *f* just coming under the brush. The latter will be nearly at the same potential as segment *e*, because segment *e* is nearly covered by it (in an actual machine). The current coming up from the right-hand side of the armature will go out, then into the external circuit by the brush across the contact surface of the latter with segment *e*. The current from the left-hand side of the armature has two alternative paths to traverse in order to get into the brush, one across the contact surface of segment *f* and the brush, the other through the coil V to segment *e*, and then across the contact surface of brush and segment *e*. It is the current taking the latter path that has to be reduced to zero and built up again.

Considering still the same instant, the motion of the coil V entering across the field of the hindward pole-horn causes an opposing electromotive-force to be induced, which we will call the "reversing electromotive-force." This electromotive-force then tends to make the current in coil V *fall* and it is aided in this by the resistance of the coil. But the falling current in the coil V produces a magnetic flux that creates an inductive electromotive-force (electromotive-force of self-induction) tending to *retard* the fall of the current. Also the current flowing across the contact area of the brush and segment *e* produces a drop of potential at that area which is small because the surface is large. The reverse is the case at the contact surface of the brush and segment *f*, because here the contact area is very small at the particular instant we are considering. Considering an instant later, the brush is making better contact with segment *f* and diminished contact with segment *e*, consequently the potential across the contact area of brush and *e* is rising above that across brush and segment *f*, and hence a current will tend to flow from segment *e* to segment *f*, that is, an electromotive-force is produced simply by the varying contact resistance, and it helps the reversing electromotive-force to do its work.

As the commutator moves on under the brush, the difference of potential between the two segments will continually increase and the combined effect of this electromotive-force, the reversing electromotive-force, and the resistance of the coil will reduce the current in the latter to zero. This should happen (for non-sparking) when the contact areas of each segment with the brush are equal. After passing through its zero value, the short-circuited coil will come under the direct influence of the flux from the backward pointing pole-horn which will induce an electromotive-force in it, producing a current in the opposite direction to what it was. This current has to grow to the original value, and is retarded in this by the inductive electromotive-force induced by its magnetic field and by the resistance of the coil. But the electromotive-force caused by the varying contact surface helps it to grow, because this electromotive-force is still in the same direction, the contact area of segment *e* and the brush continually getting less and the potential of segment *e* and brush continually rising above the potential of *f* and the brush. Finally, just as segment *e* is leaving the brush, the combined effect of the reversal electromotive-force and the electromotive-force due to the varying contact resistance, has exactly built up the current in the coil to its original strength, and therefore segment *e* will leave the brush without a spark.

II. Below three-quarter load. This is the case for which the reversing electromotive-force is too great. It is easy to see what happens for this case if we think in the light of the above of what takes place at three-quarter load, where the brushes were actually set by trial in the right position. This means that the combined effect of reversing electromotive-force and electromotive-force due to varying contact resistance did what was required. This latter electromotive-force was of course proportional to the current—that is, to the three-quarter load current. But at one-quarter load, let us say, this electromotive-force is proportionately smaller, and contributes less to the total electromotive-force required for the commuting operation. Consequently, the total electromotive-force diminishes with the load, so we may say that for any load below the load for which the brushes were adjusted the *total* reversing electromotive-force more or less automatically adjusts itself. For the greater loads, the reversing electromotive-force proper is reinforced proportionately and automatically by the drop across the contact resistances.

The above explanation * explains the process of commutation with fixed brushes. Naturally, in practice, there must be (and always is) a little sparking at very light loads and at overloads. Moreover, there is, at loads above the normal, a certain value of current which cannot be exceeded on account of sparking taking place. This is obviously at that point where the large armature reaction distorts the main field to such an extent (*i.e.* weakens the field under the hindward pole-horn so much) that sparkless collection becomes impossible.

---

* See the suggestions of Housman, *Journ. Inst. El. Engin.*, May 1893, and of E. Thomas, *Electrician*, Feb. 1898. For a fuller theoretical treatment see the two pamphlets of C. C. Hawkins (partly reprinted from articles in the *Electrician* of 1897 and 1898) on Armature Reaction and the Theory of Commutation, London, 1897, and on The Theory of Commutation, London, 1898. See also Arnold's *Die Gleichstrom-maschine*, 1902. Rothert's articles in the *Electrotechnische Zeitschrift*, 1901, 1902, are also important.

It is possible to consider the contact-surface between the brushes and the commutator as if it were the seat of an opposing electromotive-force; of the value, in the case of carbon brushes, of about 0·7 to 1 volt. Probably there is in reality no true back electromotive-force here. But if there is here (as also in the case of the electric arc), a resistance which varies, because of the variation of the area of contact, in approximately inverse proportion to the current passing through the area, such resistance will act precisely as a back electromotive-force would do. It is impossible save by some such supposition to explain the sparkless collection of current which is in fact attained in some machines with carbon brushes, *without any lead at all*, or even with a negative lead.

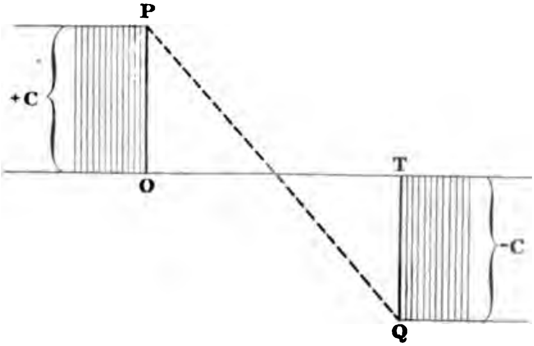


FIG. 133.—CURVE OF COMMUTATION: IDEAL CASE.

Resistance during Reversal.—Let us then assume that during commutation there is a contact resistance inversely proportional to the area of contact between the brush and the commutator. In Fig. 133 let the abscissæ measure time and the ordinates current in the coil that is to be commuted. If we reckon the zero as the instant when commutation begins and T the time when it ends, and the initial value of the current in the coil as C, then the problem is how to convert the value C into the value $-C$ during the time T. The ideal case should be that this reversal should take place by a uniform change; or, graphically, that the current curve should slope uniformly from beginning to end, the current having its value reduced to zero at a time ½ T. But this is seldom the case. Little is known as to the actual form of the curve of commutation. Messrs. Everett and Peake found in a particular machine[1] that the curves had the forms shown in Fig. 134. The curve marked A shows an initial increase (as may happen at light loads) with an oval reversal at the end. Curve B shows an under-commutation with an insufficient lead. Curve C, with an increased load, shows a rapid reversal at first, but an under-commutation towards the end of the period. Curve D shows a gradual fall, which slackens towards the end of commutation. If there were no self-induction to delay the change of current, a straight line might be obtained as the following reasoning will show. Consider a carbon brush wide enough just to cover one segment, the mica separators being for simplicity regarded as of negligible thickness. Suppose the commutator segments to be each ½ inch wide, and that the total brush length in the direction parallel to the axis is 2 inches, so that the area of brush face is 1 square inch. Suppose that it is collecting 40 amperes. These 40 amperes are made up of 20 amperes flowing in from the coils on the right and 20 from the coils on the left. Fig. 135*a* depicts the state of things when the segment A is exactly under the brush. The coil A B, which is connected between the segments A and B, carries 20 amperes flowing from left to right; and the period of commutation is just about to begin. Fig. 135*b* depicts the state of things when the commutator has moved forward through the breadth of one-quarter of a segment. The area of contact of the segment A is reduced to ¾ of a square inch,

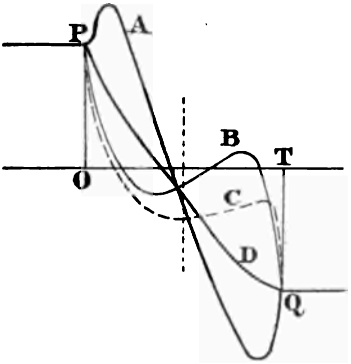
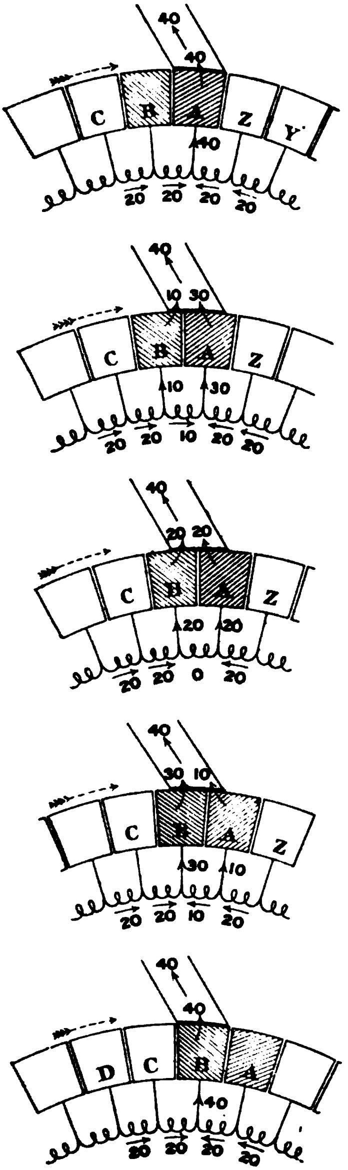


FIG. 134.—CURVE OF COMMUTATION OBSERVED BY EVERETT AND PEAKE.

---

[1] See *Electrician*, xl. p. 861, April 22; and xlii. p. 328, December 30, 1898.



a. Instant before commencement of commutation in the section A B.

b. End of first quarter of the period of commutation in the section A B.

c. End of second quarter of the period of commutation in the section A B.

d. End of third quarter of the period of commutation in the section A B.

e. Commutation in the section A B completed.

FIG. 135.—PROCESS OF COMMUTATION.

while that of the segment B has grown to ¼ square inch. Hence, assuming the coil A B itself to be of resistance negligibly small compared with the contact-resistances, the current will divide itself between the two possible paths in corresponding proportion to the areas, 30 amperes will be collected through A and 10 through B. This involves that the current carried by the coil A B has been reduced from 20 to 10 amperes. By the time the coil has moved forward through half the breadth of a segment, the contact areas of A and B will be equal, and (always on the assumption that there is no self-induction) there will be 20 amperes flowing up through A and 20 through B ; hence, as depicted in Fig. 135*c*, the current in the coil A B will have been reduced to zero. At the next stage, when the commutator has moved forward through ¾ of a segment, the contact areas as shown in Fig. 135*d* are now ¼ and ¾ and the current flowing through A is reduced to 10 amperes, while that through B has grown to 30 amperes. Hence, the coil A B must now carry 10 amperes in the reverse direction. By the end of another quarter period commutation in the section will be completed, and, as shown in Fig 135*e*, the segment A will have passed out from under the brush. The whole 40 amperes will be collected from segment B, and the current in the coil A B will have grown up to the full value of 20 reversed amperes. The operation may be graphically represented by Fig. 136, wherein the length O T represents either the time occupied by the commutation or else the actual peripheral movement through the breadth of the brush, and the height of the ordinate to any point on the line P Q will represent the value of the current in the coil at any corresponding instant measured along the line O T ; for example, at time t the value of the current would have fallen from O P to j.

It remains to consider how this ideal case will be changed by the facts (1) that the coil A B has some resistance, (2) that it has some self-induction. If the resistance of the coil be not negligible compared with the contact resistance at the surfaces, then the several amounts of current collected under the brush will not be rigidly proportional to the areas of contact. For, reference to Fig. 135 *b* will show that if the resistance of the coil A B be not zero, the resistance in the path of the current coming up through A will not be $\frac{1}{3}$ of that in the path through B. Assuming that the contact resistance over A is 0·04 ohm and that over B is 0·12 ohm; then, if the resistance of one coil be taken at the exaggerated value of 0·01 ohm, the current will divide itself as 29·4 and 10·6 amperes instead of 30 and 10; while the current in the coil A B will be 9·4 instead of 10 amperes. Briefly, the presence of resistance in the coil tends to make the commutation curve take the form of the curving line in Fig. 136.

The effect of self-induction, though difficult to reckon out quantitatively, is in every case such as to retard the fall and

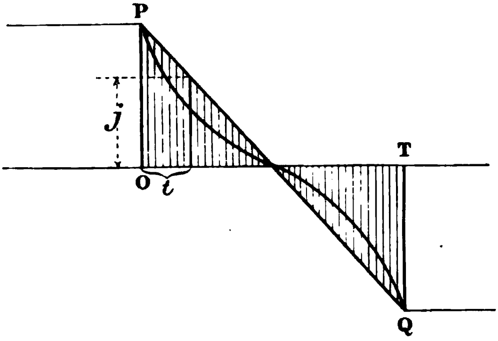


FIG. 136.—CURVE OF COMMUTATION.

reversal of the current, and would give to the current-curve a form such as indicated by the line $P L_1 Q$ in Fig. 137; or, if there is more self-induction, that of $P L_2 Q$. If at time $\frac{1}{2}$T the current in the coil is not reduced to zero, it is clear that the current-density in the contact surfaces will not be alike at all parts under the brush. For example, if at the time $\frac{1}{2}$T the current in the coil is not zero, but is still say 5 amperes, the amounts collected through the two segments B and A will not be 20 amperes each, but 15 and 25 amperes respectively. And as with the increased current density in the surface of A the contact resistance falls, this fall will of itself tend to accentuate the inequality. Moreover, if the current by reason of this retardation is not completely reversed by the end of the period T, then at the last instant as the surface of contact between the segment A and the brush diminishes down to zero, the contact resistance will rise with extreme rapidity, and the product of this resistance into the still uncommuted part of the current—graphically represented by the height of the line QU, Fig. 137, will constitute an electromotive-force between the retreating edge of the segment A and the tip of the brush. This electromotive-force it is which tends to set up a spark, and may be briefly called the *sparking electromotive-force.* In the absence of any "reversing field" to produce a forced commutation by inducing an electromotive-force to combat the retardation of self-induction, the only methods of reducing this sparking electromotive-force are (1) lengthen the period of commutation by providing a broader brush; (2) reduce the retardation of self-induction by changing the design (by shortening the axial length of the armature core, or by increasing the saturation of the teeth), so as to reduce the inductance of each coil; or (3) artificially increase the brush resistance during the last part of the period of commutation.

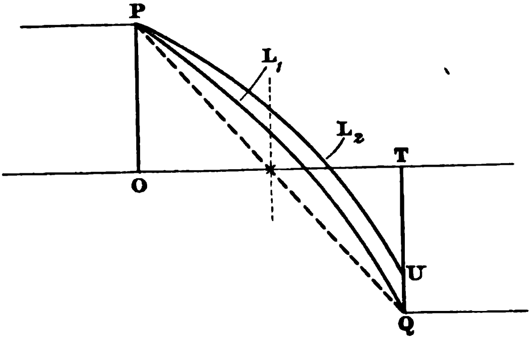


FIG. 137.—CURVE OF COMMUTATION, WITH SELF-INDUCTION.

According to Girault[1] the condition for sparkless commutation where the brush is of the same breadth as one segment, is that R_1T/L should be greater than 1; R_1 being the contact resistance under one brush, and L the coefficient of self-induction of the coil under commutation. This expression is only approximately true, and is affected by the question of the number of conductors per slot, and by the mutual induction between the adjacent conductors. It is obvious as a deduction that in a doubtful case, the commutation can be improved by increasing R_1 or T. Further considerations of a theoretical nature have been adduced by Arnold and Mie, *Elektrotechnische Zeitschrift*, xx. p. 97, 1899, and by Hawkins, *op. citat.* Boy la Tour has written a series of articles on commutation in *l'Industrie Électrique*, xi. Feb. and March 1902. The latest theory is that of Gallusser, vol. iii. of the *Sammlung elektrotechnischer Vorträge*, 1902.

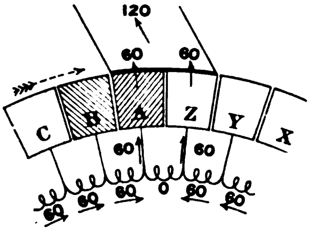
---

[1] *Bull. Soc. Internat. des Électriciens,* xv. p. 183, May 1898.

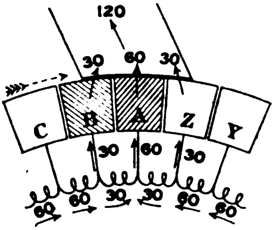
It will be seen that in this act of commutation by contact resistances, the whole process depends upon the variations of the resistance due to the increase and decrease of the surfaces of contact as they slide under the brush. *They shear off*, so to speak, *the current from the coil as it goes by, and they let into it a reversed current.* There is a certain resemblance, therefore, between this process and that of the slide-valve in a steam engine, where a variation in the area of the port-holes permits the flow of steam, or cuts it off, in its passage into or out of the cylinder.

The effect of increasing the *breadth* of the brush is not simply to prolong the period of commutation but to cause commutation to begin in one coil before it has been completed in the preceding one. This may also be considered by reference to the stages of the ideal process depicted in the series of figures from 138*a* to 138*e*.

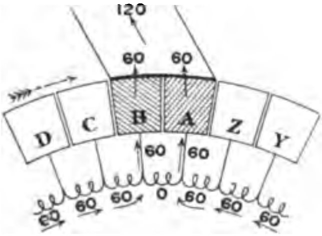
In these we suppose the brush to cover two segments, each ½ inch wide, and that the total brush length is 3 inches in the direction parallel to the axis, having therefore 3 square inches of face. Suppose also that it is collecting 120 amperes, or 40 amperes per square inch. These 120 amperes are made up of 60 amperes flowing in from the coils on the right, and 60 from the coils on the left. Fig. 138*a* depicts the state of things when the segments A and Z are under the brush.



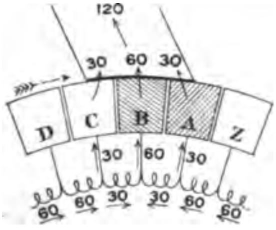
a. Instant before commencement of commutation in the section A B.



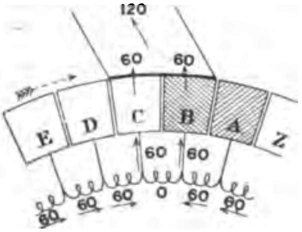
b. End of first quarter of the period of commutation in the section A B.



c. End of second quarter of the period of commutation in the section A B.



d. End of third quarter of the period of commutation in the section A B.



e. Commutation in the section A B. completed.

FIG. 138.—PROCESS OF COMMUTATION: BRUSH COVERING TWO SEGMENTS.

Their areas of contact are equal, and therefore their resistances are equal. Hence, the current flows up equally through A and Z, and there is 60 amperes flowing in the coil which is connected from A to B, which coil will from this instant begin to undergo commutation. Fig. 138*b* depicts the state of things when the coil AB has moved on through the breadth of half a segment. The areas of contact with segments B and Z are now only half of that with A; hence the 120 amperes would now be made up as follows: 60 through A, 30 through B, and 30 through Z. This involves that the current in the coil A B is now reduced to 30 amperes. In the next stage, Fig. 138*c*, the coil has moved on through the breadth of another half-segment, so that the brush covers the segments A and B. Then 60 amperes flow up through A, and 60 through B, so that the current in the coil AB has fallen to zero. At the next stage, Fig. 138*d*, 30 amperes will flow to the brush through A, 60 through B, 30 through C. Hence the coil A B must now carry 30 amperes in the reverse direction. By the time the next stage is completed A will have passed out from under the brush, and B and C will each convey 60 amperes to the brush; hence the current in A B will now be the full 60 amperes in the reverse direction, and the commutation in that section is completed. In this case where the brush covers two segments the act of commutation begins in one coil when it is half over in the next. The mutual induction between the two adjacent coils will not appreciably help the commutation. Self-induction in this case retards the process of commutation as it does in every case. In those cases where the element of the winding consists of more turns than one, the self-induction is diminished by placing the successive turns of the element in different slots, an arrangement patented by Fynn, and examined both experimentally and theoretically by Parshall and Hobart. Rothert[1] has given for the case of the brush covering one segment only, the differential equation

$$L\frac{dC}{dt} + C(r_1 + r_2 + r_3) - C_0(r_1 - r_2);$$

---

[1] *Elektrotechnische Zeitschrift*, xxiii. 865, Oct. 1902.

where L is the coefficient of self-induction of the short-circuited coil, C the current in it at any instant, C_0 the initial value of the current to be commuted, and r_1 and r_2 the two contact resistances which vary with the time, and r_3 is the resistance of the coil. In the ideal case, where the commutation curve is a straight line, $dC/dt = 2C_0/T$; and the current in the coil at the time t is equal to $C_0(1 - 4ft)$, where f is the frequency of commutation, *i.e.* the reciprocal of T. Rothert has further deduced that if the contact resistance of the brush can be so distributed that it increases toward the end of the commutation, the sparking electromotive-force under the toe of the brush will be lowered.

For discussions on the effect of commuting several sections at once by a broad brush, see Parshall and Rothert.

Use of Carbon Brushes.—Generators designed to operate with a constant lead invariably have carbon brushes. Such machines spark a good deal if metal brushes are substituted, and the above reasoning affords an explanation of this. The carbon brushes possess a much greater specific resistance, and hence the drop across them will vary greatly with the contact area. Naturally also, machines working with fixed brushes are less efficient and more costly than those operating under usual conditions, because the heat loss in the commutator is greater, and the size of the commutator has to be increased in order to get rid of the increased amount of heat.

There is some difference to be noted between the cases of shunt-wound machines, and those which are compound-wound. For in the case of compound-wound machines the magnetic excitation is automatically increased at the times when a large current has to be commuted, and this increase in the excitation helps to keep up the strength of the reversing field.

It may happen with some machines that a sparkless collection of current is impossible, wherever the brushes are set. This may be due to either (1) on account of the field system being too weak, either inherently or on account of distortion; or (2) to the inductance of the short-circuited coils being too large. If this latter is the case, even when the reversing field is amply strong enough, the operation of commutation will be nearly independent of the electromotive-force set up by the varying contact resistance, which latter will cause a waste of energy, given out mainly at the beginning and end of the commutating period, and which takes the form of strong heating of the edges of the segments, melting off the copper, and thereby drawing out an arc.

Beside the cause of ordinary sparking explained above there are some causes of an exceptional nature. In those dynamos (chiefly those used in arc lighting) that are constructed to work at high potentials approaching or exceeding 1000 volts, there sometimes occurs a phenomenon known as "flashing-over." A long blue spark will on a sudden alteration of the resistance of the circuit be drawn out around the circumference of the commutator from brush to brush. This spark, which is more of the nature of an arc, does little harm in the case of those dynamos which are constructed with commutators of few parts separated by air-gaps, but is very harmful in the case of dynamos having commutators of the ordinary sort, with thin mica insulation between the bars ; for these are easily short-circuited by the flash-over.

Practical Deductions.—The considerations above indicate the ways in which sparking may be reduced to a minimum. These are :—

1. Keeping the inductance of the armature coils low—that is, divide up the armature into many sections, so that the commutation of the current may be done in detail. In addition to this, the magnetic circuit of the flux produced by the short-circuit current in the coil should have as great a reluctance as possible. Widening the air-gap, provided the excitation is increased so as still to maintain the flux at its full value, is a remedy to reduce sparking.

2. Choosing brushes of suitable material and thickness.

3. Keeping down distortion of the main field, in order that the flux at the hindward pole-horns may be sufficiently *stiff*.

4. Proper dimensioning and design, of commutator brushes and brush-holders.

5. Providing rocker and brush gear which is in itself

mechanically substantial and rigid, while at the same time the individual "brushes" are allowed to rise and fall comparatively lightly.

6. Keeping the surface of the commutator perfectly true.

Various devices for minimising armature reaction in order to comply with requirement No. 3 above have been suggested from time to time by different designers, some of which have proved to be to a certain extent valuable in practice. Before referring to these in detail, we must consider yet another property of a loaded armature, namely, the direct demagnetizing effect of the armature current.

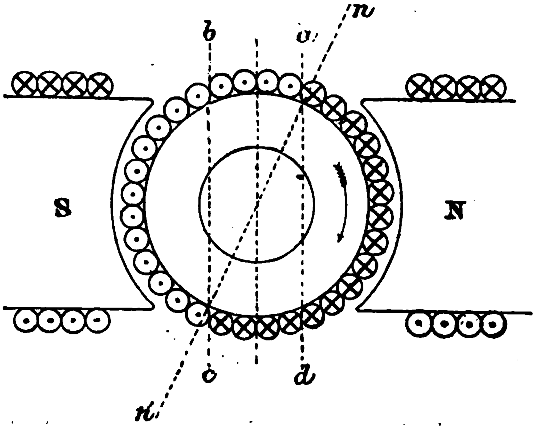


FIG. 139.

Demagnetizing Effect of Armature.—If in a dynamo there is a forward lead given to the brushes for the purpose of stopping the sparking, there at once results another reaction, namely, the production of an actual demagnetizing tendency—or back magnetomotive force. That the armature current does so act is readily demonstrated by considering Fig. 139. There the field-magnet and armature are represented as before but the brushes have been given a forward or positive lead; the neutral line *n n'* lying obliquely. The currents are flowing toward the observer in the armature conductors on the left of the neutral line, and from the observer in those on the right of that line. Now let the two lines *a b* and *c d* be drawn squarely across the armature through the points of commutation corresponding to the two brushes. These lines intersect the outline of the armature in four points. In the diagram there are thirty-two conductors spaced out around the core disk of the armature; and as this armature is drum-wound, the end connexions of the conductors will probably be somewhat like those shown in Fig. 140, where each conductor is connected across the end by a double-curved connector to the conductor that is next to the one diametrically opposite.[1] Now, so far as any magnetizing actions are concerned it does not matter what the end connexions are, provided they are compatible with the flow of current indicated above in Fig. 139, with current advancing along the sixteen conductors on the left of *n n'*, and retreating along the sixteen on the right of *n n'*. Hence we may consider them, temporarily, as grouped in any way that will assist us to understand their action. Suppose, then, that the four conductors from 29 to 32 are joined across the ends[2] to the four from 13 to 16 (Fig. 140); and let the twelve conductors from 1 to 12 be joined across to the twelve from 17 to 28. Our armature windings are now distributed into two belts, one horizontal belt of twelve

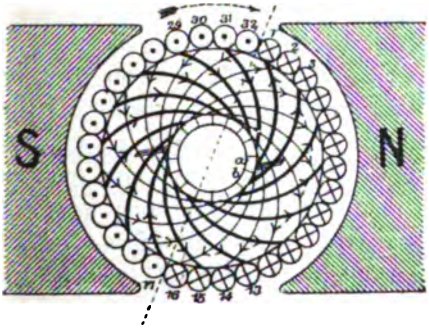


FIG. 140.
ACTUAL CONNEXIONS AT END OF DRUM-WINDINGS.

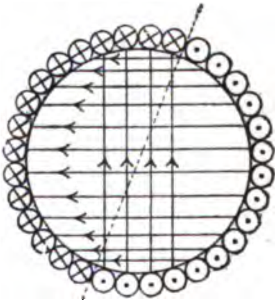


FIG. 141.—CONDUCTORS GROUPED INTO CROSS-MAGNETIZING AND DEMAGNETIZING BELTS.

---

[1] For modes of connecting drum-windings, see Chapter XIII.

[2] See Swinburne in *Journal Inst. Elec. Engineers*, xv. 542, 1886.

windings which tends simply to *cross-magnetize*, and one vertical belt of four windings, Fig. 141, which tends simply to *demagnetize*; for it will be seen that the direction of the circulation around the vertical belt is opposite to the direction of the circulation of current in the magnetizing windings. The breadth of the belt of demagnetizing windings is obviously proportional to the angle of lead, since it subtends double that angle. If the armature in question were carrying 100 amperes then, since there are two paths through the armature circuit (pp. 201 and 208) each conductor must carry 50 amperes. Hence the number of cross-magnetizing ampere-turns is 50 × 12 = 600; and the number of demagnetizing ampere-turns is 50 × 4 = 200.

Now the cross-magnetizing action which, as we have seen, distorts the field, does of itself slightly diminish the flux of magnetic lines that crosses the armature core from side to side, because in the oblique resultant direction of the magnetization the increased flux tends to produce greater saturation in the pole corners. For other researches on the effect of a cross-magnetism in diminishing the magnetism of the core, see papers by Siemens[2] and Schültze[3] in *Wiedemann's Annalen*. Schültze, in the course of twenty-four experiments, found that the cross-magnetization of an iron core always diminished the longitudinal magnetization. More recent experiments on these effects are those of Frölich, Kennelly[4] and Stromberg.[5]

In a Manchester dynamo, tested by Prof. Ayrton,[5] 5846 ampere-turns of excitation were needed when no lamps were on, and 10,000 when the machine was furnishing its full output of current: of the additional 4154 ampere-turns, 1754 were needed to compensate for the lost volts (due to internal resistance and lessened permeability) and 2400 to compensate for the demagnetizing effect of the armature current with the increased lead needed to prevent sparking. The greater the

---

[1] Werner Siemens, *Wiedemann's Annalen*, xiv. 634, 1882.

[2] Schültze, *Wied. Ann.*, xxiv. 663, 1885. See also Oberbeck, *Habilitations-Schrift*, 1878.

[3] *Electrician*, xxv. 111, 1890.

[4] *Centralblatt für Elektrotechnik*, 1887, 283.

[5] *Journal Inst. Electrical Engineers*, xix. 175, 1890.

lead given to the brushes in a dynamo used as a generator, the greater is the demagnetizing effect of the armature current. In motors the direction of the armature current is opposite to that in the dynamo (that is to say is *against* the electromotive-force), a negative or backward lead has to be given to the brush to avoid sparking—and this backward lead also results in a demagnetizing tendency. If a negative lead (*i.e.* a displacement from the neutral line in the opposite direction to the sense of the rotation) is given to the brushes of a generator the magnetizing effect of the armature currents will tend to assist the magnetization of the core. Drs. J. and E. Hopkinson[1] have shown that if a backward lead is given, a generator can excite itself by means of the armature currents only ; but in such case of negative lead there was a destructive amount of sparking. The demagnetizing effect is of course proportional to the number of effective ampere-turns of the armature circuit that surround the magnetic circuit, and therefore to the actual number of ampere-turns included, as we have seen, in a belt of double the angular breadth of the angle of lead.[2] According to Kapp a smaller actual number of compensating turns is required in practice. Another method of regarding these distortions is as follows.

The number of "ampere-conductors" under any pole-face can be calculated by counting the number of conductors under the pole-face at one time, and multiplying by the current that each has to carry. This number, if multiplied by $4\pi \div 10$ gives the cross-magnetizing magnetomotive force. If we take the number of conductors that lie at any time between the tips of two adjacent poles, and multiply by the current which each has to carry, we similarly obtain the number of ampere-conductors that tend to demagnetize, on the assumption that the lead is such that commutation occurs just at the pole-tip.

---

[1] *Phil. Trans.*, 1886, part i. p. 347.

[2] According to Peukert, who, however, does not specify the angle of lead, the demagnetizing effect of the armature current is proportional to the 1·3 power of the armature current. See *Centralblatt für Elektrotechnik*, ix. 484, 1887. According to Karpen (*Comptes Rendus*, cxxxiv. 827, April 1902, the demagnetizing reaction has a maximum at a certain value of the excitation.

The interference of the armature with the magnetization of field-magnets may also be studied in relation to the "characteristic" curves of dynamo machines (see Chap. XII.), which are used to show the rise of the electromotive-force of the machine in relation to the corresponding strength of the current; this rise being proportional to the magnetization through the armature. Now the characteristics of nearly all series-wound dynamos show a decided tendency to turn down after attaining a maximum; and in some machines, for example the older form of Brush arc-light dynamo with cast-iron ring, this reaction is very marked. The electromotive-force diminishes, though the magnetizing force of the field-magnet coils goes on increasing. The effect is due partly to the distortion of the magnetism, but mostly to the demagnetizing effect as the lead of the brushes is increased. It is at least significant that in the older form of Brush machine, where the reduction of electromotive-force is very great, there is also such a mass of iron in the armature, and so variable a lead at the brushes.

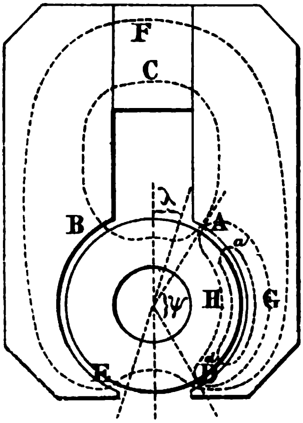


FIG. 142.
ARMATURE INTERFERENCE.

In the paper referred to above Dr. Hopkinson[1] treated the theory of armature interference as follows.

In Fig. 142, draw any closed curve A B C A along the magnetic circuit so that it passes through the magnetizing coils. The line integral of the magnetizing forces along this line will be equal to $0 \cdot 4 \pi$ times the ampere-turns in the coils (page 78). There will be an equal magnetomotive-force around the closed curve D E F D, though the resulting flux along this path may be less, owing to the greater reluctance.

---

[1] Drs. J. and E. Hopkinson, *Phil. Trans.*, 1886; also reprint of Hopkinson's *Original Papers*, 1893, 105.

Similarly, if the brushes are advanced with an angular lead λ, the number of conductors in the demagnetizing zone will be a fraction $2\lambda \div \pi$ of the whole number Z on the armature, and as each carries half the current, the demagnetizing ampere-turns (for drum-winding) will be

$$\tfrac{1}{2} C_a \times \tfrac{1}{2} Z \times 2\lambda \div \pi = \lambda C_a Z \div 2\pi,$$

and the demagnetizing magnetomotive-force will be $0{\cdot}2\,\lambda\, C_a Z$. Further, the tendency to cross-magnetize may be calculated by considering the closed curve H A G D H drawn through the pole-tips of one pole-piece. If the angle of polar span be called ψ, the number of conductors enclosed by this curve will be $\psi Z/2\pi$, and the line integral of the cross-magnetizing forces will be $0{\cdot}4\pi \times \tfrac{1}{2} C_a \times \psi Z/2\pi = 0{\cdot}1\,\psi C_a Z$. As the reluctance in the parts of this path which pass through iron is negligible, we may regard the whole of this as expended on the gaps at A and D; and it will be seen that the difference of magnetic potential at the gap A will be diminished, and that at D increased, by half this amount. Since any smaller closed curve, as at *a d*, encloses few conductors, it will produce a proportionately smaller distorting effect. The minimum field required for reversal in the neighbourhood of the pole-tip depends both on the current to be reversed, on the self-induction of the "section," and on the time occupied in the act of commutation. The cross-force which tends to diminish the field of the region A must not be suffered to reduce the field below the necessary minimum. This is then Hopkinson's theory of the reversing field. It expresses, however, only half of the truth. For, if it were the whole truth no machine could possibly commute sparklessly at all loads with fixed brushes, nor could any machine run sparklessly on any load if its brushes are set (as in many tramcar motors and in some boosters) with no lead either way. The theory takes no account of the contact resistance at the brushes, or of its variation, which we have seen plays a vital part in the operation of commutation. Nevertheless, this theory is useful for the study of the cross-magnetizing and demagnetizing reactions. It will be noted that the demagnetizing reaction (which is proportional to λ) tends to weaken the field in general, while the cross-magnetizing reaction tends (which is proportional to ψ) to weaken the field under the hindward pole-tips, and to strengthen it under the forward tips. In order that we may be able to reverse sparklessly very great currents, we must have the impressed field so strong that at least the minimum field remains at the pole-tip in spite of both these reactions. Seeing, then, that the cross-field is responsible for the distortion which makes sparkless collection difficult, it remains to consider the remedies. These may be classified under two heads—those applied to the magnets, and those applied to the armature. The former class may again be sub-classified; for in dealing with the cross-field we have two courses open, either to increase the reluctance in the path or to introduce a compensating counter cross magneto-motive-force.

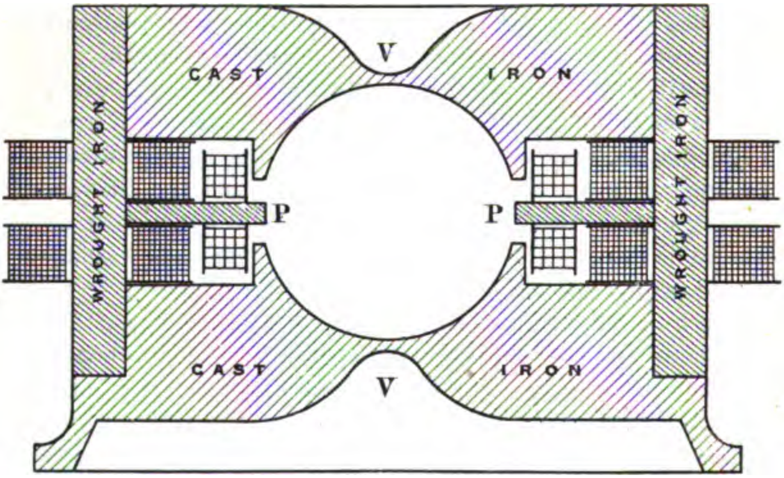


FIG. 143.—MAGNET WITH V-GAPS AND COMPENSATING POLES (Sayers).

Cross-Reluctance Remedies.—Any gap introduced across the closed path H A G D H of the cross forces will diminish the cross-field; hence merely widening the clearance of the armature will to some extent help; but then more winding will be wanted on the magnet-cores. The polar mass behind the face may be nearly divided by a "V" groove; as is readily done in the case of magnets of the Manchester type (No. 24, Fig. 60) and other forms having double magnetic circuits (as No. 8, Fig. 59 and Fig. 69) by judicious thinning, or by actual separation, as in No. 27, Fig. 60, between the right and left-hand halves, and so throttle the cross-flux of magnetic lines. To prevent weakening of the structure a thin web is left in the casting, as in Fig. 143. Another suggestion, made by the author of this work some years ago, was to construct the field-magnets of pieces of iron, with longitudinal gaps, as in Fig. 144. This idea, or modifications of it, may be seen embodied in many modern constructions, including some of the most recent railway generators of the Westinghouse Company.

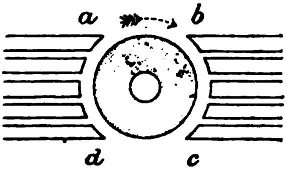


FIG. 144.

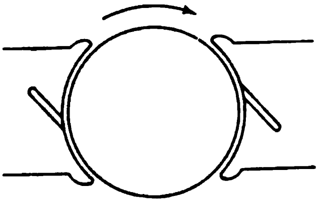


FIG. 145.

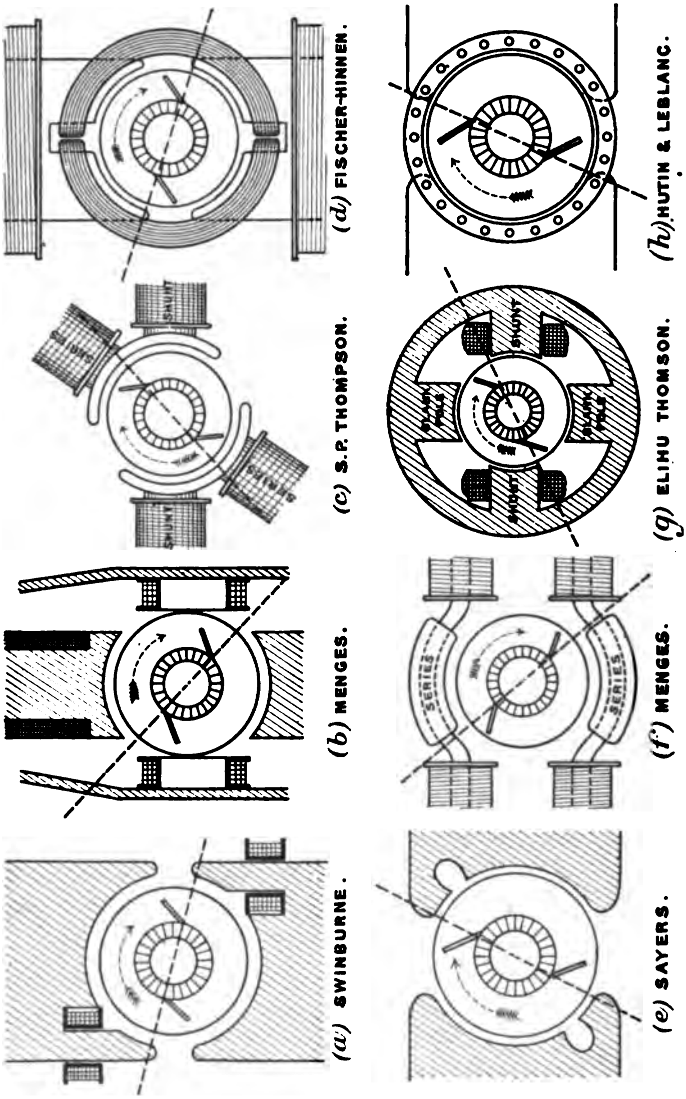
Another modification proposed by the author is to slot the pole-piece obliquely, as shown in Fig. 145; for then the neck of the casting becomes highly saturated and offers great reluctance, and tends to prevent distortion.

The device shown in Plate XIII. is due to Fischinger of Dresden. The forward pole tip is made of cast iron, bolted obliquely to the pole core which is of cast steel.

Cross Compounding Remedies.—Elihu Thomson proposed to place a compounding coil on a separate frame surrounding the armature, and to tilt it in a direction counter to the rotation so as partially to counteract the cross force. Swinburne[1] suggested that a small auxiliary coil (in series) should be wound upon the tip of the pole, as in Fig. 146*a*, to maintain a reversing field at that point. Mather,[1] Housman,[2] and Swin-

---

[1] *Journ. Soc. Teleg. Engineers*, xv. 542, 1886.



(*a*) SWINBURNE. (*b*) MENGES. (*c*) S.P. THOMPSON. (*d*) FISCHER-HINNEN. (*e*) SAYERS. (*f*) MENGES. (*g*) ELIHU THOMSON. (*h*) HUTIN & LEBLANC.

FIG. 146.—VARIOUS DEVICES FOR SPARKLESS COLLECTION OF CURRENT.

---

[1] *La Lumière Électrique*, xix. 404, 1885.

[2] *Journ. Inst. El. Engineers*, xx. 299, 1891.

burne[1] have all advocated the use of auxiliary poles at right-angles to the main poles (as in Fig. 143), wound with main circuit coils to counteract the armature force. The author of this treatise suggested a sort of compound winding having series and shunt poles at different angles (Fig. 146*c*) so that as the armature reaction tended to shift the field forward, the field should automatically shift itself back. Menges,[2] in 1884, proposed a cross compound winding having the auxiliary series coils set to produce a field at right angles (Fig. 146*b*) to the ordinary field. He also suggested winding series coils around the polar parts of a machine with double magnetic circuit, as in Fig. 146*f*. Fischer-Hinnen[3] winds these coils in a notch at the centre of the pole-face (Fig. 146*d*), a construction which independently occurred to Prof. Forbes, to Mr. Mordey and the author.

Prof. Elihu Thomson[4] has proposed yet another solution (Fig. 146*g*), in which, by the use of auxiliary unwound poles presented, at right angles, to the armature, he leads off the cross-flux into the back of the wound poles, and uses it to strengthen the field, instead of weakening it.

The most complete solution, however, is that given by Prof. Ryan,[5] who inserts a number of coils in slots cut in the pole-face parallel to the shaft, to receive a series winding, which thus constitutes approximately a neutralizing layer of coils with a circulation of current equal and opposite to that of the armature. Fig. 147 shows a design of Ryan's with the coils arranged in slots. In such machines[6] the magnetization does not drop with the load, nor does the neutral point shift. Further, the gap-space may be made very small, reducing the weight of the field windings. The entire absence of distortion of field at all loads is a gain; but for absolutely sparkless collection it seems better to provide a special commuting field than to depend on finding one somewhere in the fringe near the pole-tip. This Ryan proposes to accomplish as shown in Fig. 148 by bridging the space between the poles C D by an iron structure, slotted at *k l m n o p*, to receive the compensating conductors, and provided with a special commutating lug *g* in the centre of these windings. At no load this lug is not magnetized; but as load increases the excess of

---

[1] See Swinburne (*Journ. I.E.E.*, xxx. 105, 1890); and Housman (*ib.*, xx. 299, 1891), who maintained that if $\mathfrak{B} = 7000$ under the pole-piece, the auxiliary field for reversing must be at least = 3000. [2] D. R. P. No. 34,465.

[3] *Berechnung elektrischer Gleichstrom-maschinen* (Zürich, 1892).

[4] *Electrical Review* (N.Y.), xxvii. 18, July 1895.

[5] "On a Method of Balancing Armature Reaction," *Sibley Journal of Engineering*, vii. 17, Oct. 1892; see also Ryan and M. E. Thompson, *Am. Inst. of Electrical Engineers*, 1895, where tests are given of such machines; reprinted in *Electrician*, xxxiv. 765, April 19, 1895. See also *Electrician*, Jan. 14, 1898, for an article by J. Fischer-Hinnen relating to this method.

[6] See Oerlikon High Speed Generator, Fig. 482.

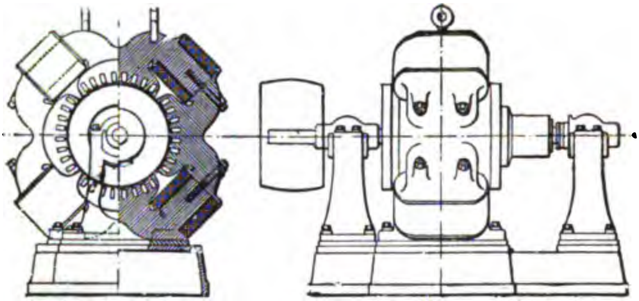


FIG. 147.—RYAN'S DYNAMO, WITH CROSS-COMPOUND COILS.

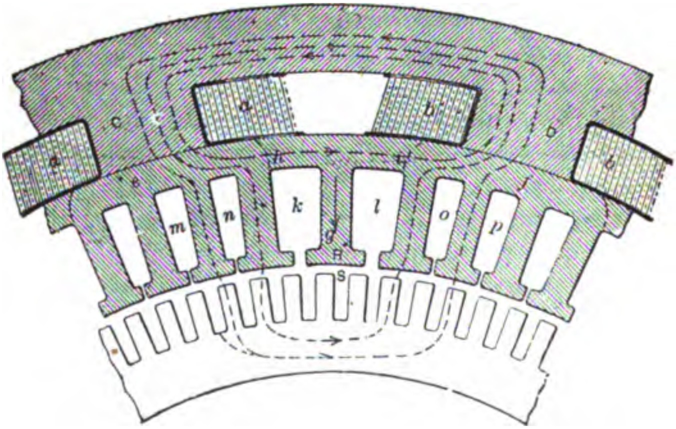


FIG. 148.—RYAN'S COMPENSATING DEVICES.

ampere-turns in these compensating windings over the cross ampere-turns of the armature tends to magnetize g in the direction of the arrow, giving a commutating field always proportional to the current to be commutated. Deri has recently revived this proposal, using as field-magnet a laminated structure resembling the stator of a two-phase motor.

The device of Hutin and Leblanc, Fig. 146*h*, called an *amortisseur*, consists of a series of rods of copper carried through slots in the pole-faces, all short circuited together at their ends like an embedded squirrel-cage. This device is supposed to prevent oscillations in the direction of the magnetic flux which occur at commutation. It can be usefully employed also with alternate-current machines, as when used in this connection it greatly facilitates good parallel running.

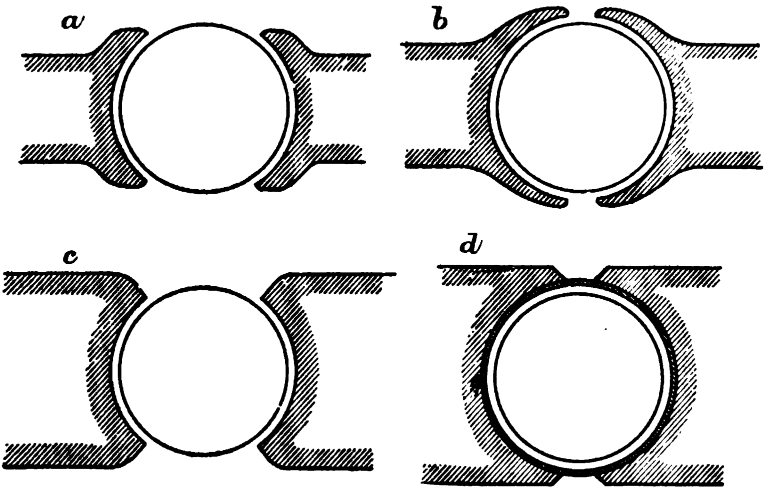


FIG. 149.—VARIOUS FORMS OF POLE-TIPS.

Concentration of Field.—There are other methods of preserving the requisite concentration of field at the leading edge of the pole. It is obviously desirable that the field should be magnetically *rigid*—not easily distorted. This stiffness of field can be partially secured by judicious shaping of pole-pieces. A simple notch in the pole-face, as in Fig. 146*e* promotes concentration of the field in the tip. If the tip is itself nearly saturated, the tendency to distortion may produce less effect than if it were far from saturation. But it is not on this account worth while to make the tips of cast iron instead of wrought, as they then saturate with a less flux. Tips widely separated, like Fig. 149*a*, are not always good, even though thin. It is better that they should either be extended like Fig. 149*b*, nearly to meet, so that they may be saturated by the leakage field, or else cut off like Fig. 149*c*. Dobrowolsky has recommended the *bushed pole* (Fig. 149*d*), in which the armature is completely surrounded with iron.

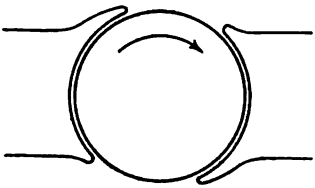


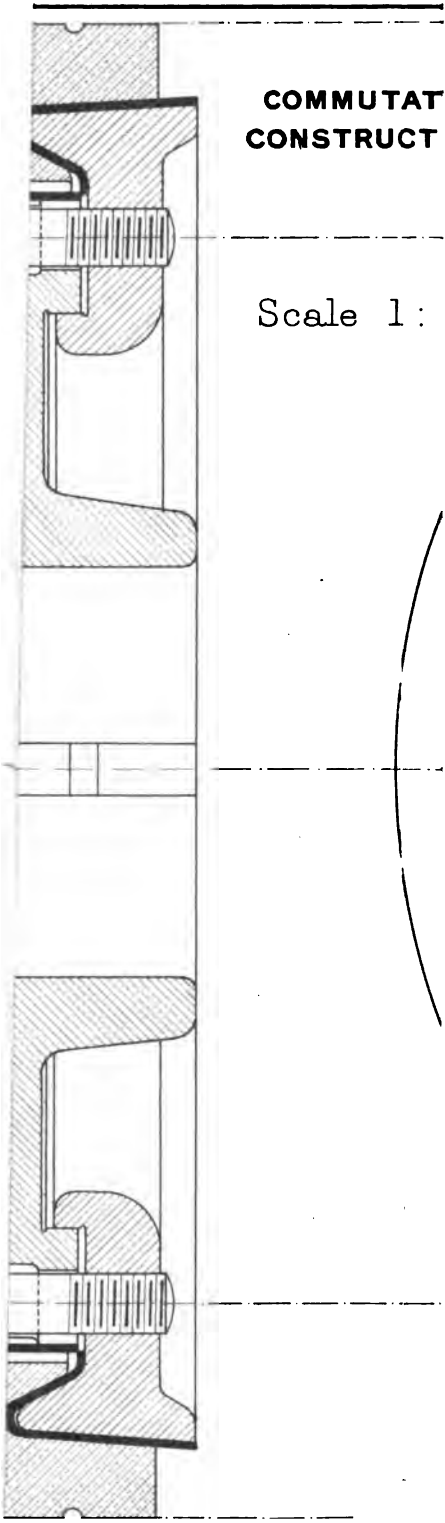
FIG. 150.

In the eighties M. Gravier proposed the unsymmetrical form of pole-piece shown in Fig. 150; the forward horn being elongated, the hindward horn truncated. When the machine is working at small loads the field in the gap is nearly uniform: but at great loads with distorting reactions having a tendency to drive the flux into the forward pole-horn, the small section of the latter causes it to become saturated, thus minimising distortion.

Mr. Lundell has combined with this device the method of slotting the pole; and has produced the form shown in Fig. 151, which is said to answer well, and to enable a fixed position to be given to the brushes.

A simpler plan still is to make the pole-shoes of cast iron, while the cores are of cast steel, or of iron plate (see p. 691).

These forms differ very greatly as to the width of *fringe* which they permit in the field. It is of advantage that the field should present, where the conductors enter, a margin in which the flux-density varies from zero to a high value. If this margin is too narrow, the neutral point will be very well defined, and the brushes need very accurate adjustment. If it is too wide, the variations of lead at different loads may be excessive. One way of securing a suitable fringe, and at the

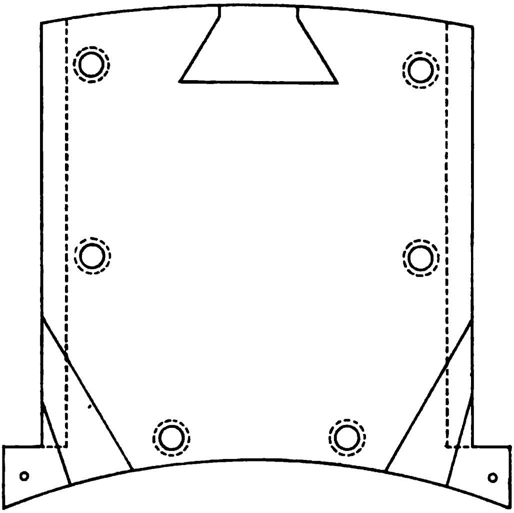


COMMUTAT
CONSTRUCT

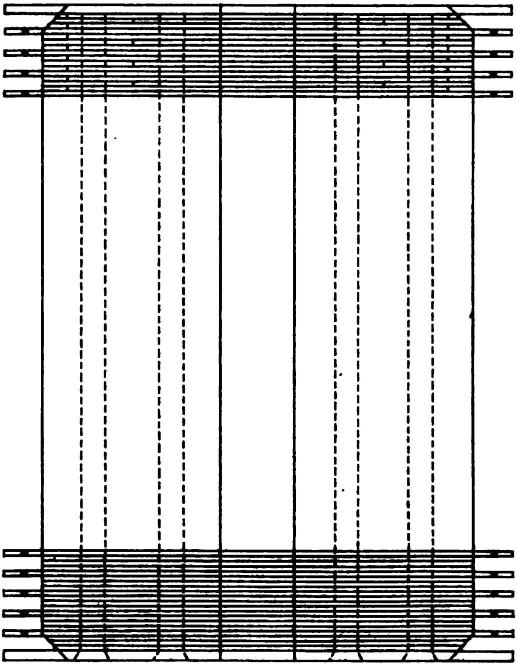
Scale 1:

Plate XXIII.

POLE LAMINATIONS



Scale ⅓



Thoᵉ Kell & Son, Ltd.

same time maintaining fair rigidity against distortion, is to bore the polar faces to a different and flatter curve, so that the polar gap is narrowest at the middle and wider at entrance and exit, as in Fig. 152. Another way, which has been found excellent by Mr. Brown, for his well-known multipolar machines (Fig. 403), is to make the inwardly projecting poles of circular section, without any pole-shoes or extensions. The end-face of the pole when bored away presents a sufficient lip, and secures a well graduated field of sufficient stiffness. See also Fig. 450, p. 713.

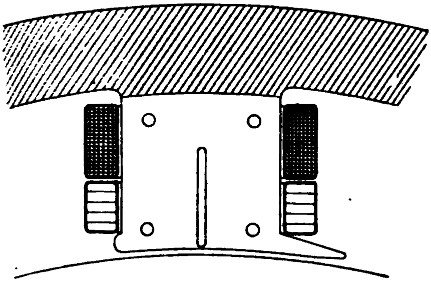


FIG. 151.
LUNDELL'S FORM OF POLE.

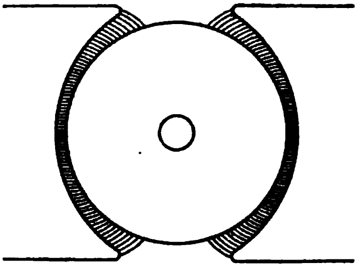


FIG. 152.
NON-CONCENTRIC POLES.

Another device for securing a gradual entrance of the armature conductors into the field is to give to the hindward edge of the pole-shoe an oblique direction. This is to be seen in the dynamo of Kolben, Plate XVIII., and Fig. 153*a*, and in many of Schuckert's machines. Other makers shape away the pole-shoes with polygonal ends, as in Parshall's machine, Plate X., p. 680, and Fig. 153*b*, or with clawed ends as in the machine of the English Electric Manufacturing Co., Fig. 442, p. 693, and Fig. 153*c*. A recent type of Ganz and Co. with laminated pole-tips cut away in alternate layers, is depicted in Plate XXIII. In the two last cases the extra saturation of the tips helps to prevent distortion.

Mr. W. R. V. Marshall has proposed[1] to attain saturation by attaching groups of short laminated iron plates, with narrow spaces between, thus reducing the nett section while preserving nearly as much effective pole surface.

---

[1] Specification of Patent No. 18530 of 1901.

Self-compensating Armatures.—Turning to armature methods of compensation, we find several devices. Swinburne's chord winding (p. 354) diminishes the demagnetizing but not the cross-magnetizing force. It has the disadvantage that the two edges of any section are not both passing at the same instant into a commutating field; hence it is not good for handling large outputs in machines with small clearance. Its service is to create a machine which up to its spark-limit has so little demagnetizing reaction that the excitation does not require to be increased to keep up the pressure as the load increases. A modified chord winding for use with slotted armatures has met with considerable success at the hands of Mr. Mordey,[1] who claims for it many advantages.

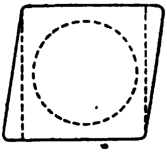


FIG. 153*a*.

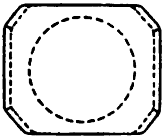


FIG. 153*b*.

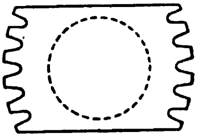


FIG. 153*c*.

The best suggestions are those of Sayers,[2] who connects the bars of his commutator to the appropriate point on the ring or drum winding, not directly in the ordinary way by radial connectors, but through auxiliary compensating coils wound also upon the armature. One of these *commutator coils* is shown in Fig. 154, one end being attached to the junction between two main armature coils and the other end being attached to a commutator bar. At the instant before the bar comes in contact with the brush the whole armature current is being carried by a commutator coil immediately ahead of the one shown in the figure. When the heel of the brush touches the bar, the left side of the commutator coil belonging to it is well under the pole-piece, so that it tends to take up the current; while the commutator coil preceding it has its right side just coming under the auxiliary pole tending to stop the current in it and reverse it in the intermediate main armature winding. The commutator coil in Fig. 154 has just taken up the current. A moment later its right side will come under the auxiliary pole, which will stop the current in it and pass it on to the next commutator coil. Sometimes the auxiliary pole is wound as shown in Fig. 143. The main advantage of Sayers' winding is that instead of putting the brushes forward he is able to give them a backward lead so that the armature current exercises a helpful magnetizing action and obviates the need of any compound winding on the field-magnets.

---

[1] See *Journal Inst. E.E.*, vol. xxvi. No. 130.

Inst. Elec. Eng., July 1893, xxii. 377; 1895, xxiv. 122; and xxvi. 597, May 1897.

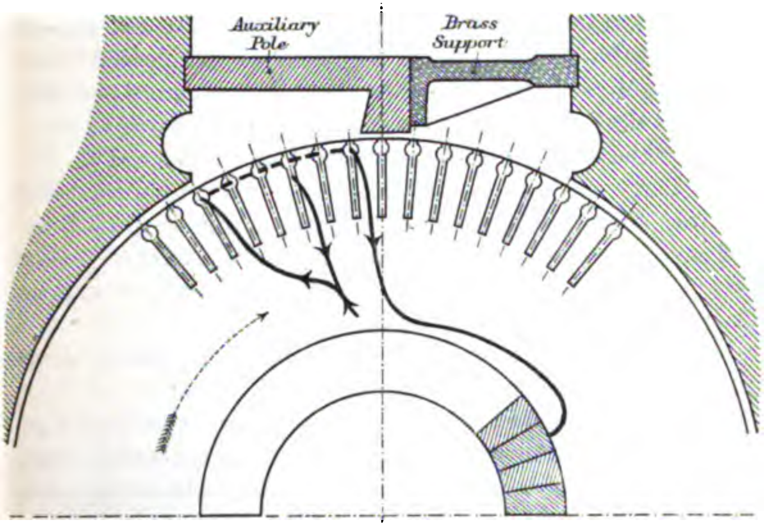


FIG. 154.—SAYERS' COMPENSATING WINDING WITH COMMUTATOR COILS.

Hobart has discussed[1] the relation of brush-position to armature interference, in which he investigates the possibility of giving generators a backward lead so as to be self-compounding.

---

[1] *Electrical Review*, l. 329, Feb. and Mar. 1902.

It is an open question whether the employment of any of the more elaborate devices enumerated above can come commercially into use, except, perhaps, for machines of moderate output. An examination of the largest machines of the present day, about which there can be no question as to successful operation, invariably shows that the heating limit is reached before the point at which sparking occurs. The freedom from sparking is obtained by careful designing and by multipolar construction. The special points to be attended to are:—

1. The reacting ampere-turns per pole must not exceed certain fairly definite values in machines of a given type. A safe figure is 10,000 armature ampere conductors per pole, provided the average volts per segment do not exceed 10; or 20,000 if the average volts per segment do not exceed 5.

2. Large air-gaps are unnecessary if the armature teeth are very highly saturated, for this tends to diminish both de- and cross-magnetization. A flux-density in the teeth of 20,000 to 23,000 (apparent) lines per square centimetre or 125,000 to 150,000 per square inch is appropriate.

3. Armatures should be as short as possible in the axial direction, in accordance with condition (2), p. 250.

4. The inductance of the short-circuited coils must be small in comparison with the contact-resistance, while at the same time the current-density in the brushes used must not exceed certain well-defined limits.

From the nature of things these constants are not independent of one another.

Reactance Voltage.—Great stress has been laid by Mr. Parshall upon the importance of the quantity which he terms *reactance voltage*[1] and which he regards as the vital consideration in determining whether a machine of given design will or will not commute its current sparklessly. The fundamental idea is as follows. During the act of commutation the current in any one section of the winding must first die down to zero, and then reverse and increase up to its former value. This reversal of the current in the section takes a certain time. Now we know that all increase and decrease of the current in any conductor is opposed by the self-induction of that conductor, and that if the conductor lies—as the conductors of armatures usually do—largely surrounded by iron, the self-induction of the conductor will make it act as a choking coil to retard the reversal of the current by counter-electromotive forces. And, just as one can in the case of choking coils calculate the voltage due to the reactance evolved by any specified alternating current of known frequency, so, *if we assume that the variations of the current during the act of commutation may be represented by a half-period of an alternating current,* we can also in this case calculate the reactance-voltage, provided the coefficient of self-induction of the loop of conductor under commutation be also known. In the case of a choking coil in which the coefficient of self-induction is L henries the current C amperes, and the frequency of alternation n periods per second, the reactance voltage is equal to $2\pi n L C$. To apply this calculation to the commutation of a dynamo we have to learn first how to calculate (*a*) the equivalent frequency of reversal, and (*b*) the coefficient of self-induction. If we divide the breadth of the brush by the peripheral speed of the commutator we ascertain the time taken for the reversal of the current; and doubling this time gives us the equivalent "period," the reciprocal of which will be the equivalent frequency. Further, if we estimate the number of magnetic lines that are generated in the surrounding space (iron and air) by one ampere in one inch length[1] of the conductor, we can calculate thence the number of self-induced lines for the actual loop by multiplying by the current in it and by the length of its embedded part. If more than one turn is being commuted at one time under the brush we must also multiply by that number. To reduce the number of lines to henries we must divide by 10^8. Having thus all the data, the calculation of the reactance-voltage is simple.

---

[1] Parshall and Hobart, *Electric Generators* (1900), p. 175.

Example: This is taken from the case of the 10-pole tramway

---

[1] Parshall gives four lines per ampere per centimetre for an embedded conductor, and 0·8 lines for a conductor free in air. Rothert gives 8 lines per ampere per centimetre, which is 20·3 lines per ampere per inch, for an embedded conductor.

generator described on p. 678 (Parshall's 550 kw.). This machine has a parallel-wound armature with 300 slots, 6 conductors per slot, and carrying 100 amperes. The commutator has 900 segments, with one turn of winding per segment. The commutator diameter is 86 inches; its periphery 272 inches; and at 90 revolutions per minute its peripheral speed is 408 inches per second. The carbon brushes are about 0·8 inch wide, and therefore cover about three segments of commutator at one time. Hence three loops or six conductors are short-circuited at one time. The gross length of the core-body is $20\frac{1}{2}$ inches. So we calculate as follows:—

Assuming 25 lines per ampere per inch of embedded conductor, the flux surrounding 1 conductor 20·5 inches long, will be 512·5 lines per 1 ampere; or for 6 conductors 3075 lines per ampere. Dividing by 10^8 brings this to 0·00003075 henry as the coefficient of self-induction. The time taken to reverse the current will be 0·759 (*i.e.* 0·8 inch, less the thickness of one piece of mica) divided by the peripheral speed of 408 inches per second, or 0·00196 second = $\frac{1}{510}$ second. This is one reversal, equal to half a "period." The duration therefore of the "equivalent period" is $\frac{1}{254}$ second, whence the equivalent "frequency of commutation" is 254 per second. Hence by formula $E = 2 \pi n L C$, we find the reactance-voltage to be $2\pi \times 254 \times 0{\cdot}00003075 \times 100 = 3{\cdot}9$ volts.

Now, assuming that there is a reactance-voltage thus generated in the loop during commutation, it is clear that in order to effect reversal in spite of this opposing electromotive-force, there must be imposed upon the loop some induced electromotive-force at least as great. This reversing electromotive-force is that due to commutation occurring in the fringe of the polar field. To make certain that reversal shall take place in the time allowed for the act of commutation, the reversing electromotive-force ought, therefore, to be considerably greater than this reactance-voltage. In the example given above where the reactance-voltage was found to be 3·9 volts, the *average* electromotive-force generated, per segment of the commutator, was 6·1 volts.

The objection to this use of the "reactance-voltage" as a criterion is that it is based upon an assumption, not justified in fact, that the variation of the current during the time of commutation follows a sine-curve. The researches of Everett and Peake[1] and those of H. N. Allen,[2] show that the variation is more complicated, and that in general the reaction-voltage will be higher than that calculated on the assumptions named. Further, the presence of an induced electromotive-force sufficient to overcome the reactance-voltage depends not on the *average* electromotive-force per segment of the commutator but on the particular electromotive-force induced in the loop while it passes through the fringe of the polar field.

Hobart has shown[3] that the self-induction of the "free" portions of the armature conductors which are not embedded in the slots, may be considerable. In many multipolar armatures the length of the "free" part may be three or four times the length of the "embedded" part; and as the inductance (per ampere per inch) of the free part is from ¼ to ⅙ part of that of the "embedded" part, it follows that the actual inductance of the "free" part may constitute from 25 to 40 per cent. of the total inductance of a loop.

Rothert gives rules for calculating reactance-voltage, which are equivalent to the following:—

$$e_r = 60 \times 10^{-8} \times \frac{g \times \mathrm{K}w \times (l'' + 0{\cdot}1\, l''_2)}{\mathrm{N} \times p};$$

$$e_r = 105{\cdot}6 \times 10^{-8} \times \frac{\mathrm{Z}^2 \times \text{revs. p. m.} \times \mathrm{C}_1 \times (l'' + l''_2)}{\mathrm{K}};$$

where g is the number of conductors in one element of the winding; l'' the length of the embedded part; and l''_2 that of the free part of one conductor; Kw the output; C_1 the current in one conductor; and N, K, Z and p have their usual significations.

The opinion of designers seems to be that if copper brushes are used the reactance-voltage must not exceed about half the average electromotive-force per segment, while with carbon brushes it may be 1·2 times as great in dynamos, or 1·8 times as great in motors.

---

[1] *The Electrician*, xl. 861, Ap. 22, 1898; and xlii. 328, Dec. 30, 1898.

[2] *Journ. Inst. El. Engineers*, xxvii. 209, April 1898.

[3] *Ib.*, xxxi. 170, Sept. 1901; an important paper with valuable experimental investigations, and discussion.

Sparking Criterion.—Based upon experience with certain types of machines, many designers are able to predict from the working drawings and data whether a given machine will carry its rated load sparklessly or not, and the empirical rules used in this connection are frequently of very great value if properly used. A rule that has been much used by designers, and which is moreover very easy to apply, is that the flux-density under the backward pole-horn shall not be less than 20,000 lines per square inch for ring and 13,000 for drum armatures. That is to say, if X_g denotes the ampere turns per pair of poles required for the double air-gap, and X_c denotes the cross-magnetizing ampere-turns (equal to the number of conductors lying under one pole multiplied by the current in them), then

$$B_g \times \frac{X_g - X_c}{X_g} \overset{=}{>} 13{,}000 \text{ to } 20{,}000$$

where B_g is the flux-density in the air-gap in lines per square inch. For railway or similar motors, in which the direction of rotation requires to be reversed, the constant must be taken higher, and is of the order of 25,000 to 30,000. But although such an empirical rule may give good results with machines of a particular type, whose winding and magnetic constants do not vary very much with size, it is clear that its sphere of application is limited, and moreover, it must be used with caution in every case.

A rule which is found satisfactory in the design of large generators for traction and lighting, working at 400 to 600 volts, is this :—that if the design is such that not more than 200 amperes are to be collected at any one set of brushes, if the average flux-density in the gaps is not less than 40,000 lines per square inch, and if the teeth are well saturated, the machine will run sparklessly *if the number of ampere-conductors does not exceed* 650 *per inch of the periphery* of the armature. The number of *ampere-conductors per inch of periphery* varies, in the machines described in this book, from 350 to 700.

Parshall mentions a 12-pole machine in which the value was 728, and a 10-pole machine in which it reached 840; but neither of these machines would run sparklessly at all loads with fixed brushes.

A good criterion is *the ratio of the flux-density in the gap to the ampere-conductors per inch of periphery.* The former has usually values approximating to 50,000, while the latter is usually from 500 to 600. This ratio is, therefore, of the order of magnitude of 80 to 100. It may be briefly called the *stiffness-ratio.* If higher, the machine is unnecessarily heavy; if lower, it may be prone to spark at high loads.

Another criterion of goodness of commutation is the value of the stiffness-ratio as compared with the volts per segment of the commutator. The latter varies (see p. 483) in machines of different voltages. In 100-volt machines the voltage per bar may be taken as about 3. In these, then, the stiffness-ratio (of 80 or 100) divided by the volts per segment gives the *commutation-ratio* as from 27 to 33. In 500-volt machines, taking voltage per bar as about 6, gives 13 to 16 as the commutation-ratio. Any lower values than these should be looked upon with suspicion.

Yet another criterion is to compare the number of ampere-turns of excitation needed at full load to drive the flux through the gap and teeth, with the whole number of ampere-conductors (at full-load) that lie under one pole-face. This is a comparison in effect between the magneto-motive force that can resist distortion, with the ampere-turns tending to distort the field. A couple of examples from machines known to commute well at all loads will suffice:—

In Parshall's 550 kilowatt generator, p. 678, the number of ampere-turns spent on gap and teeth is 6600 per pole, while the distorting ampere-conductors under one pole amount to 14400, making the ratio of the former to the latter 0·45.

In the Scott and Mountain 150 kilowatt generator, p. 582, the ampere-turns for gap and teeth amount to 8350, while the distorting ampere-conductors are 13000, making the ratio 0·64.

Mr. Kapp has suggested two other criteria, involving the use of arbitrary coefficients, which are here stated in British units.

Let B_3 be the flux-density (lines per square inch) in the gap,
„ X_0 be the number of ampere conductors per inch of armature periphery,
„ K be the total number of commutator segments,
„ k_2 be the number of commutator segments short-circuited together by any one brush,
„ Y_1 be an empirical numeric,
„ Y_2 be a second empirical numeric,
„ g be the length across one air-gap (iron to iron), in inches,
„ d be the diameter of the armature, in inches.

Then the *first* criterion is that

$$Y_1 = B_3 \times k_2 \div X_0 ;$$

where for good results, in

slotted drum armatures, Y_1 should not come less than 38
„ ring „ „ „ „ 60

The *second* criterion is that

$$Y_2 = Kg \div d(1 + k_2) ;$$

where for good results

with metal brushes, Y_2 should not fall below the value 1·2
„ carbon „ Y_2 „ „ „ 0·6

It may be taken that carbon brushes will commute sparklessly, without any lead, provided the design is such that if the machine is run at normal speed, short-circuited, and excited to such a degree that it generates normal current on short-circuit, there is not generated more than 2 volts between two segments as they pass the neutral point; for the voltage-drop at the brush can compensate 2 volts without having any reversing field.

CHAPTER XI.

ELEMENTARY THEORY OF THE DYNAMO. MAGNETO, AND SEPARATELY-EXCITED MACHINES. SELF-EXCITING MACHINES.

IN all that follows, the armature is regarded merely as consisting of a certain number Z of conductors, grouped in a particular way around an axis of rotation, their function being to cut across the magnetic lines that are furnished by the magnetic circuit. The symbol N stands for the *magnetic flux per pole*; that is *the whole number of magnetic lines that cross the air-gap to or from any one pole*; the strength of all the poles being assumed to be equal.

The number of *revolutions per second* made by the armature is denoted by the symbol *n*. It is found that the average electromotive-force generated by the armature is simply proportional to each of these quantities, so that by taking the appropriate units we may write, as will presently be seen, for the fundamental equation

$$\text{(average) } E = n\, Z\, N \div 10^8 \quad . \quad . \quad . \quad [\text{I.}]$$

In the present chapter is first found this expression, which serves as the fundamental equation. Then by introducing appropriate formulæ for the various circuits, equations are deduced for the various kinds of series-wound, shunt-wound and compound-wound dynamos.

SYMBOLS USED.

It may be well to point out that in this and the succeeding chapter the following symbols are used in the following significations:—

b	number of external wires in a section of the armature.	
C	current in external circuit,	expressed in *amperes.*
C_a	current in armature,	
C_m	current in series coil or main circuit,	
C_s	current in shunt coil,	
c	number of circuits in parallel through an armature.	
K	number of segments of commutator.	
E	entire electromotive-force generated in an armature,	expressed in *volts.*
e	the lost volts or potential drop,	
	efficiency, nett or commercial (see pp. 297 and 521)	
η_1	economic coefficient, or electrical efficiency.	
η_2	gross efficiency, or efficiency of conversion.	
F	force (i.e. push or pull), expressed in either *dynes*, *poundals*, *grammes'* weight or *pounds'* weight.	
L	coefficient of self-induction.	
λ	angle of lead.	
M	volts per revolution per second, or *effort-factor.*	
μ	magnetic permeability of iron.	
N	the magnetic flux, or whole number of magnetic lines from one pole.	
n	number of revolutions *per second.*	
ν	coefficient of magnetic dispersion, or of allowance for magnetic leakage.	
p	number of poles.	
R	resistance of external circuit,	expressed in *ohms.*
r_a	resistance of armature coils,	
r_s	resistance of shunt coils,	
r_m	resistance of series coil on field-magnets,	
r	internal resistance of dynamo,	
S	number of spirals or turns of wire in coil.	
S_m	number of turns in a main circuit coil, in series with armature.	
S_s	number of turns in a coil in shunt.	
T	torque, or turning moment, or angular force, or couple, expressed in *dyne-centimetres*, *gramme-centimetres*, *metre-kilogrammes*, or *pound-feet*, according to circumstances.	
t	time measured in *seconds.*	
v	surface speed in *feet per minute.*	
V	volts at terminals of dynamo or motor.	
W w	activity, or power, or work-per-second, expressed in *watts* or in *horse-power.*	
Z	number of conductors on armature, counted all round the periphery.	
ψ	angle of pole span.	
ω	angular velocity (expressed in *radians*-per-second).	

FUNDAMENTAL EQUATION OF DYNAMO.

To find the average electromotive-force of a moving conductor, we must remember that, by definition, see page 59, this is (in absolute C.G.S. units) numerically equal to the number of magnetic lines that are cut in one second by the conductor. Also the practical unit, the *volt*, being by definition equal to 10^8 absolute C.G.S. units of electromotive-force, it will be necessary to divide the number of C.G.S. units by 10^8 in order to reduce the number of lines per second to volts. Further, as there are in all armatures a number of conductors in series with one another, the total electromotive-force of the dynamo will be equal to the sum of the electromotive-forces of those conductors that are in series with one another. The fundamental equation of an ordinary dynamo with ring or lap winding will then be written :—

$$\text{(average) E (in } volts\text{)} = n \, \text{Z} \, \text{N} \div 10^8 \quad . \quad . \quad \text{[I.]}$$

Let the number of "sections" in the armature winding be denominated by the symbol K; the number of "segments" or "bars" in the commutator or collector will also be K. Let there be in each section b external wires or conductors, as counted on the outside of the armature core. (In ring-armatures there will be the same number of external wires as there are loops or windings in the section; in drum-armatures there are twice as many external wires as there are loops or windings in the section.) Then the number of external conductors or wires, reckoned all round the armature, will be $b\,\text{K}$; it will be more convenient to use the single symbol Z for this number. The number of external conductors or wires that are in series with one another electrically from brush to brush will be $\frac{b\,\text{K}}{c}$ or $\text{Z} \div c$. Now let the armature rotate with a speed of n revolutions per second. (Engineers usually count the revolutions made in one minute, necessitating division by 60 to get n). Then one revolution will take $\frac{1}{n}$ part of

1 second. We are now ready to calculate the electromotive-force.

No. of lines cut by 1 *external wire in* 1 *revolution* . . . . $= pN$

(because each wire cuts all the lines under all the poles);

No. of lines cut by 1 *external wire in* 1 *second* . . . . . $= npN$;

No. of lines cut by Z/c *external wires in series in* 1 *second* . . . $= np \times NZ \div c$;

No. of lines cut by Z/c *external wires in series in* 1 *second* . . . . $= nZN\frac{p}{c}$.

Average electromotive-force (in C.G.S. units) . . . . . $= nZN\frac{p}{c}$.

Average electromotive-force (in *volts*) . $= \frac{nZN}{10^8} \cdot \frac{p}{c}$. [1*a*.]

Whence, in all parallel-wound armatures, where there are as many circuits through the armature as there are poles,

Average electromotive-force (in *volts*) . . $= \frac{nZN}{10^8}$. . [1*b*.]

For brevity this may be written

$$E = nM; \quad . \ . \ . \ . \ . \qquad [1c.]$$

where M stands for $\frac{p}{c} \cdot \frac{ZN}{10^8}$; being the number of volts at a speed of one revolution per second on the supposition that the magnetic flux is maintained. The interesting thing about this quantity M is that torque per ampere is also proportional to it. It may be called the *effort-factor*.

For many purposes it is more convenient to have the fundamental equation in terms of the angular velocity. Let the symbol ω represent the angular velocity. Then $\omega = 2\pi n$; for, in each revolution, the angle described is 2π *radians* or 360 *degrees*. Consequently $n = \omega / 2\pi$, which gives;

$$\text{(Average) } E = \frac{\omega}{2\pi} ZN \div 10^8. \quad . \ . \ . \qquad [1d.]$$

It will be observed that this electromotive-force is simply an average; and it depends on the construction of the armature how much fluctuation there is in the value during a rotation.

If, as in Fig. 155, the armature had but two external conductors forming a simple loop, then the electromotive-force would fluctuate between zero and a maximum. Calling the lowest point of the rotating loop in its vertical position 0°, then the position on the left of the dotted line will be 90°, if we reckon the rotation in the clockwise direction. The top point will be 180°, and the point on the extreme right 270°. Then the induced electromotive-force will be zero as the coil passes through 0° and 180° (for at the positions 0° and 180° the conductors will be sliding along, rather than cutting, the magnetic lines), and a maximum as the coil passes through 90° and 270°. The *rate* of enclosing or "cutting" will be a *maximum* when the *actual number* of lines enclosed is a *minimum*, and *vice versa.* (See page 200.)

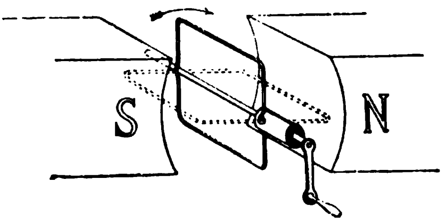


Fig. 155.—Ideal Simple Dynamo.

At any intermediate angle, if the field is uniform, the actual number of lines of force enclosed is proportional to the cosine of the angle through which the coil has turned from its zero position, and the electromotive-force will be proportional to the sine of the angle. Strictly speaking, we ought to take the sine with a *negative* value to represent the electromotive-force, because as usually defined the induced electromotive-force is proportional to the rate of *decrease* in the number of lines of force enclosed. We need not, however, trouble about signs, because, if the brushes are properly set at the commutator, all the induced electromotive-forces are thereby made to act in the same direction through the external circuit. The angular velocity being $2\pi n$, the angle passed through in an interval of time of t seconds will be $2\pi n t$. Calling this angle θ, and reckoning it from the lowest point as before, the electromotive-force in the loop at any time t may be calculated as follows:—The number of lines of force enclosed when the loop has turned through angle θ is $= \mathrm{N} \cos \theta = \mathrm{N} \cos 2\pi n t$; hence the rate of cutting will be $2\pi n \mathrm{N} \sin \theta$. Now, since the average value of $\sin \theta$, between the limits $\theta = 0°$ and $\theta = 90°$, is $2/\pi$, the *average* electromotive-force *per loop* may be obtained by substituting this value, giving us

$$\text{Average E per loop} = 4 n \mathrm{N} \text{ lines per second.}$$

The number of loops that are in series between brush and brush is $\frac{1}{2}$ Z, in a bipolar armature. Inserting this, and dividing by 10^8 to reduce to volts, we have finally

$$\text{(Average) E, in volts} = n \mathrm{Z} \mathrm{N} \div 10^8.$$

If the coil consisted of many turns all wound in one group, like the Siemens shuttle-wound armature, p. 46, the same expressions would obviously hold good on substituting the proper number for Z.

Fluctuations of Electromotive-force.—As explained above, the actual induced electromotive-force is proportional to the sine of the angle through which the coil has turned, or

$$\mathrm{E} = 2\pi n \mathrm{N} \sin \theta \times \tfrac{1}{4} \mathrm{Z} \div 10^8,$$

whence

$$\mathrm{E} = \frac{\pi}{2} n \mathrm{Z} \mathrm{N} \sin \theta \div 10^8 \quad . \quad . \quad . \text{[II.]}$$

As θ increases from 0° to 360°, the value of the sine goes from 0 to 1, then 1 to 0, from 0 to -1 and from -1 back to 0. The values of the sine are depicted in Fig. 156. The same curve may serve then to show how the electromotive-force would fluctuate if there were no commutator. But the action of the commutator is to commute the negative inductions into positive ones; the brushes being so arranged as to slide from one part of the commutator to the other at the moment when the inverse induction begins. This gives the curve the form of Fig. 157, which therefore represents how the voltage pulsates in the circuit of a simple old-fashioned shuttle-wound Siemens armature. Now if we could level these hills, and change our undulating induction into a steady one, we should get a single straight line, shown in Fig. 157 as a dotted line enclosing below it a rectangular area equal to the sum of the areas enclosed by the sinuous curves, and therefore at a height which is the average of the heights of all the points along the curves; in fact, since each sinuous curve is part of a curve of sines, the *average* height will be $2/\pi$, or about 0·637 of the maximum height. In consequence of self-induction in the coils, the current will not actually fluctuate[1] as much as the voltage, the hollows being partly filled.

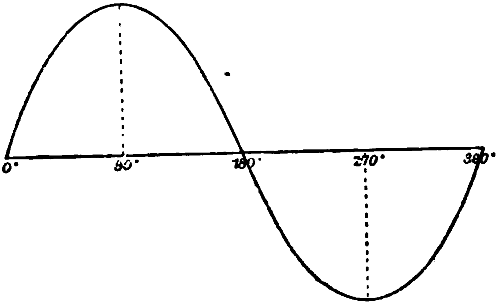


FIG. 156.

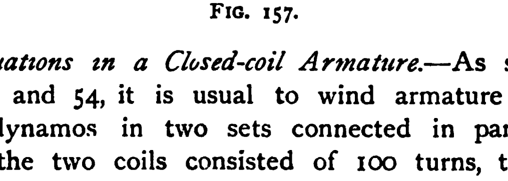


FIG. 157.

Fluctuations in a Closed-coil Armature.—As shown on pages 53 and 54, it is usual to wind armature coils for bipolar dynamos in two sets connected in parallel. If each of the two coils consisted of 100 turns, their joint effect in inducing electromotive-force would be no greater than that of either of them separately, but the internal resistance of the armature would be halved. From this point onwards in the argument it will be assumed that the armature windings consist of *pairs* of coils. Thus, instead of one coil of 200 turns, as shown in Fig. 158, we shall take it that there is a pair of coils each of 100 turns, as in Fig. 159.

---

[1] See remarks by Cromwell F. Varley in *Phil. Mag.*, 1867, and by Puluj in *Sitzungsber. Wien. Akad.*, II*a*, May 1891.

Now suppose that, in order to get a less fluctuating effect, we divide each of our original single pairs of coils into two parts, and set these at right angles to one another. To take a numerical case, suppose there were originally 100 turns in each coil, and we split each into two coils of fifty turns, but set them across one another so that one comes into the best position in the field as the other is going out of it. (This arrangement is indicated in Fig. 160, which may be contrasted with Fig. 33.) In this case we shall have two sets of overlapping curves, each of which will have to be but half as high as before, because the equivalent area of each coil is only half what it was for the whole coil. Then, if there were no commutator, the induced electromotive-force in the two sets of coils would fluctuate as shown by the two curves of Fig. 161, which differ by a quarter period from one another. But if the ends of the two "sections" of the coil are joined to a proper commutator, all the "inverse" inductions will

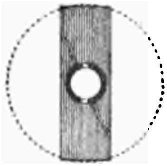


FIG. 158.

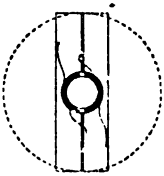


FIG. 159.

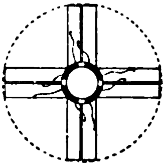


FIG. 160.

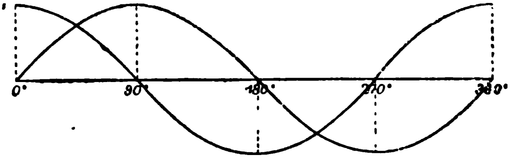


FIG. 161.

be commuted into "direct" ones, and the two curves would then become as in Fig. 162. The next process is to ascertain what the joint result of these overlapping electromotive-forces will be: it is evident that from 0° and 90° the two inductive actions are assisting one another, and that at 45° they are equal. The curve representing the *sum* of the two curves is given in Fig. 163. This curve shows at once a step towards *continuity*, as the fluctuations are far less than those of the single coil, Fig. 157. If, as before, we level the undulating tops by a dotted line, we get precisely the same height as before. The *total* amount of induction (the total cutting of lines per second) is the same, and the *average* electromotive-force is the same. There is no gain, then, in the total electric work resulting from rearranging the armature coils in two sets at right angles to each other; but there is a real gain in the greater continuity and smoothness of the current.

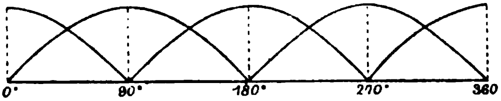


FIG. 162.

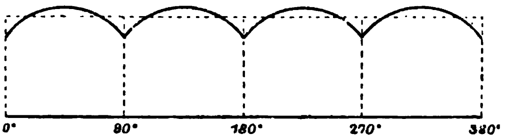


FIG. 163.

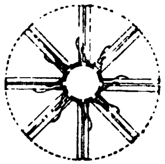


FIG. 164.

If we again split our coils and arrange them as shown in Fig. 164 at angles of 45°, in four sets of pairs of coils of twenty-five turns each, and connect them up to a proper commutator, we shall get an effect which is very easily represented by constructing two curves, each similar to the last but each of half the height, and compounding them together (Fig. 165). One of them will of course have the maximum heights of crests occurring 45° further along than those of the other curve; and when these are compounded together we get for a resultant a curve shown in Fig. 166, which has exactly the same *average* height as before, but which has still less of fluctuation. It is easily conceived that this process of dividing the coil into sections, and spacing these sections out at equal angles symmetrically, would give us a result approaching as near as we choose to an absolutely continuous one. If our original pair of coils of 100 turns each were split into twenty sets of pairs of five turns each, or even into ten sets of pairs of ten turns each, the approach to a continuity would be very nearly truly attained.

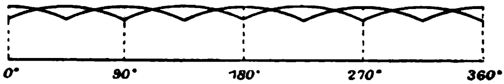


FIG. 165.

Calculation of Fluctuations.—If the variations of the electromotive-force literally followed a sine law, it would not be difficult to calculate the amount of fluctuation when a commutator with any particular number of segments is used. Some calculations on this basis given in previous editions showed that with a 20-part commutator the fluctuations were less than 1 per cent. of the whole, and with a 36-part commutator they were less than $\frac{1}{5}$ of 1 per cent. But as a matter of fact the distribution of the field in the part where coils are commuted does not obey any such law; and in the absence of

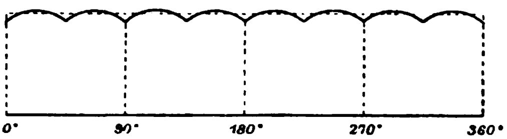


FIG. 166.

information as to the exact way in which the induction of electromotive-force varies in the fringe of the field, such calculations may be very wide of the mark. It suffices to know that a 20-part commutator in a bi-polar field gives fluctuations that are practically negligible, so that if it were not for other considerations—such as avoidance of sparking—it would be a useless refinement to employ commutators having more numerous segments.

Measurement of Fluctuation.—The relative amount of fluctuation in the current furnished by a dynamo may be observed by noticing the inductive effect on a neighbouring circuit into which is introduced a Bell telephone receiver. If the current is steady there will be no sound heard. If it fluctuate, each fluctuation will induce a corresponding secondary current in the telephone circuit, and the amount and frequency of the fluctuations may be estimated by the loudness and pitch of the sound in the telephone. The fluctuations in the current of a Brush arc-light dynamo are in this manner readily detected.

Effect of Non-simultaneous Commutation.—If the brushes are not so set that the sliding of contact under one brush is not accomplished at the same instant as that under the other brushes, then it is clear that there will be slightly unequal electromotive-forces in the different paths in the armature circuit. This momentary inequality will die out, to be succeeded by another inequality (of opposite sign) when commutation occurs at the other brush. The effect will be the same as though a small alternating current having n K periods of alternation per second were made to act around the circuit of the armature. Such effects may be occasioned in armatures by various causes; if the number of sections in an armature be an odd number; if the number of conductors in all the sections are not alike or their connexions are unsymmetrical; or, lastly, if the contact edges of any of the brushes do not lie exactly at the neutral points.

Measurement of the Flux N.—An important problem is how to measure the actual number of magnetic lines that pass through the armature. This number is really best ascertained by calculation from the performance of the machine itself. The speed being observed by aid of a suitable speed-counter, the number of conductors round the armature being known, and the whole electromotive-force generated in the machine being measured by proper electrical methods, then it only remains to apply the fundamental formula, transformed so as to calculate back to N :—

$$\mathsf{N} = 10^8 \times \mathrm{E} \div n\mathrm{Z}.$$

To measure E while the machine is running, it must either be run upon known resistances (so as to enable E to be calculated by Ohm's law); or E may be calculated by measuring (see p. 203) the difference of potentials at the brushes with a voltmeter, and then calculating from the resistance of, and current in, the armature the volts lost internally, which, added to the measured volts, make up the whole E, see equation [IV_a.], p. 293.

It must be noted that for armatures with series-grouping (p. 282), where c is less than p, the preceding formula becomes :—

$$N = \frac{10^8 \times E \times c}{npZ}.$$

Voltage per Unit Length of Winding.—Consider a conductor 12 inches long cutting across a magnetic field of which the density is 50,000 lines per square inch, at a speed of 2500 feet per minute or 500 inches per second. It will cut the lines at the rate of 300,000,000 per second, or in other words will generate 3 volts. A loop made up of two such conductors properly arranged would generate 6 volts. This is broadly the case of a loop in the armature-winding of a multipolar dynamo, but the average electromotive-force would be less than 6 volts, since the poles do not cover the whole armature periphery. But 5 volts per loop is quite a common value with ordinary peripheral speeds. This is about 5 inches length of *active conductor* per volt. But owing to the presence of air ducts a more usual figure is 6 to 7 inches per volt.

THE MAGNETO MACHINE AND THE SEPARATELY-EXCITED MACHINE.

In magneto machines, in which the field is due to permanent magnets of steel, N depends both on the magnetism of the steel and on the iron core of the armature. The number of lines that find their way through the armature is, however, lessened by the reaction of the armature when a current is being drawn from the machine. If the magnetizing forces of the field-magnets were so overpoweringly great, as compared with that due to the armature coils, that this reaction was insignificantly small, then, by equation [I], the voltage would, for any given magneto machine, be directly proportional to n, the speed of rotation. But we know in practice that this is not the case. The number of turns by which the speed, at any output, exceeds the number that would be needed for strict proportion is called the *dead turns*.

Suppose we turn a magneto machine at 600 revolutions per minute ($n = 10$, for then there will be 10 revolutions per second) and get, say, 17 volts of electromotive-force from it, then if there were no reactions from the armature, turning it at 1200 revolutions per minute ought to give exactly 34 volts. This is never quite attained; though in many machines the direct proportion holds nearly good, so long as no current is drawn from the machine to give rise to demagnetizing effects. In that case the only reaction which would cause departure from proportionality is that possibly due to eddy-currents. If the speed and the total volts generated in the armature are observed, and plotted out against one another, the straightness of the "curve"—which ought to be a straight line sloping down to the origin—will show how nearly the theoretical condition is attained.

If the current in the armature is kept constant by increasing the resistances of the circuit in proportion to the speed, the demagnetizing action of the armature can be kept constant, even though the machine is giving out current.

In some experiments[1] made by M. Joubert at different speeds, the electromotive force was measured by an electrometer which allowed no current whatever to pass, and the theoretical law was almost exactly fulfilled. The observations are given below.

Speed	500	720	1070	revolutions per minute.
Electromotive-force	103	145	208	volts.

Potential at Terminals of a Dynamo. Lost Volts.—The potential at terminals of the magneto machine—and indeed of every generator—is, when the machine is doing any work, less than E, the total induced electromotive-force, because part of E is employed in driving the current through the resistance of the armature. The symbol V is used for the difference of potential between terminals. Only when the external circuit is open, so that no current whatever is generated, V = E. It is convenient to have an expression for V in terms of the other quantities, seeing that when any current is being generated it is impossible to measure E directly by a voltmeter or by an electrometer, whereas V can always be so measured.

Let r be the internal resistance of the machine, that is to say, the total resistance of the armature coils of the commutator connexions, of the brushes, and of any main circuit windings on the magnets ("series coils" or "compounding coils") which may be in circuit between the terminals; and let R be the resistance of the external circuit. Then, by Ohm's law, if C be the current,

---

[1] See also experiments by Mordey, *Journal I.E.E.*, xix. 233, 1890.

$$E = C\,(r + R).$$

Also, the volts required to drive the current C through the internal resistance r, will be,

$$e = C\,r.$$

But by Ohm's law also, if V be the difference of potential between the terminals of the part of the circuit whose resistance is R,

$$V = C\,R;$$

whence

$$\frac{V}{E} = \frac{R}{r + R}; \quad . \quad . \quad . \quad . \quad \text{[III.]}$$

also

$$V = \frac{R}{r + R} \times E.$$

It is also convenient to note that

$$E = \frac{r + R}{R} \times V;$$

for this formula enables us to calculate the value of E from observations of V made with a voltmeter. But often the values of R are unknown: hence the following is more useful.

$$V = E - e$$

or

$$V = E - C\,r. \quad . \quad . \quad . \quad . \quad . \quad \text{[IV.]}$$

This is equivalent to saying that the volts at the terminals are equal to the whole volts generated in the armature less the volts needed to drive the current C through the internal resistance r. The volts $C\,r$ which are thus not available in the external circuit, are called *lost volts*: they will be less the smaller the internal resistance is. Equation [IV.] may be transposed to :—

$$E = V + Cr. \quad . \quad . \qquad [IV.]$$

If V is observed by a voltmeter, then E can be found by adding the lost volts; and these can be calculated by measuring the amperes flowing through the armature and multiplying them by the internal resistance. In good modern dynamos the lost volts at full load do not amount to more than 2 or 3 per cent. of the whole voltage. The percentage is often spoken of as the *pressure-drop*.

Relation between whole Electromotive-force and Difference of Potentials at the Terminals.—The essential distinction pointed out above between the whole electromotive-force E,

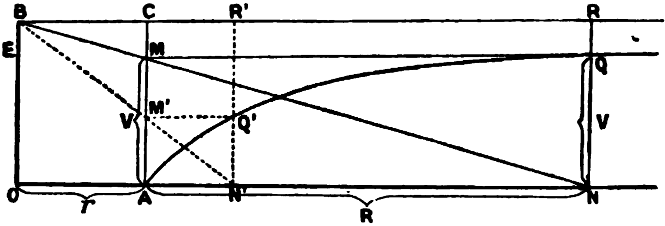


FIG. 167.

and that part of it which is available as a difference of potentials at the terminals V, may be further illustrated by the following[1] geometrical demonstation.

In a machine (such as are chiefly dealt with later) in which V is constant, E will not be constant, except in the unattainable case of a machine which has no internal resistance.

And if E is constant, then V cannot be constant when C varies. We have then two cases to consider :—

(1) E *constant.*—Take resistances as abscissæ and electromotive-force as ordinates, and plot out (Fig. 167) $OA = r$, $AN = R$, $OB = E$. The line BN represents the fall of potential through the entire circuit. Of the whole electromotive-force OB, a part equal to CM is expended in

---

[1] *Elektrotechnische Zeitschrift*, iv. 161, April 1883.

driving the current through the resistances r, leaving the part A M available as the difference of potential at the terminals, when the total resistance of the circuit is represented by the length from O to N. Accordingly, at N erect a vertical line N Q equal to A M. Take a less external resistance $R' = AN'$ and by a similar process we find that the corresponding value of V is A M′ or N′ Q′. Similarly, any number of points may be determined; they will all lie on the curve A Q Q′, which therefore shows how, as the external resistance is increased, the terminal potential rises, whilst the whole electromotive-force remains constant and is represented by the horizontal line B R. The equation of this curve is given by the condition

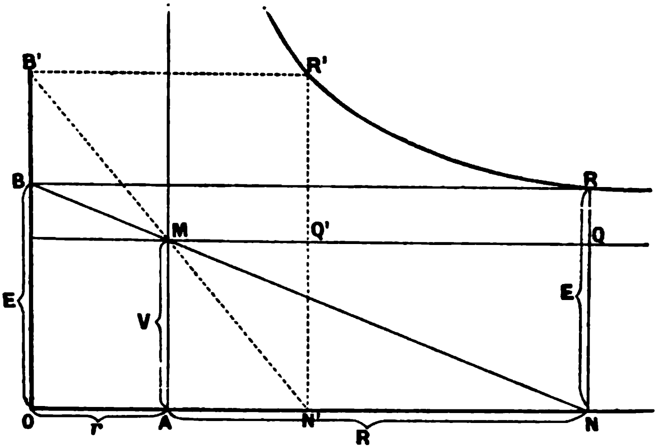


FIG. 168.

$$\frac{E - V}{E} = \frac{r}{R + r},$$

whence $(E - V)(R + r) = E r =$ constant; which equation is the equation of an equilateral hyperbola having O B and B R as asymptotes.

(2) V *constant.*—As in the preceding case, $OA = r$; $AN = R$; and $AM = V$. From N (Fig. 168) draw the line N M and produce it backwards to B. Then O B represents that value of E which will give V volts at terminals when

R = N M. Accordingly set off at N the line N R = O B. In a precisely similar way draw N′ B′ to correspond with any other value of R, and make N′ R′ equal to O B′. N′ R′ represents the value of E when the value of the external resistance R is equal to A N′. By determining other values we obtain the successive points of the curve R R′, which shows how the whole electromotive-force must vary in order to maintain a constant difference of potentials at the terminals, as represented by the horizontal line M Q. The equation to this curve (also an equilateral hyperbola) is given by the condition

$$\frac{E - V}{r} = \frac{V}{R}$$

or

$$(E - V)\,R = V\,r = \text{constant.}$$

The Separately-excited Dynamo.—For separately-excited dynamos the same formulæ hold good as for magneto machines; but in this case **N** depends upon the strength of the independent exciting current.

In estimating the nett (or commercial) efficiency of a separately-excited dynamo, the energy spent per second in exciting the field-magnets ought to be taken into account. The loss in excitation may amount to as little as 1 per cent. of the total output, in large machines; or, in small machines to as much as 3 per cent.

EFFICIENCY AND ECONOMIC COEFFICIENT OF DYNAMOS.

Suppose that we know the actual mechanical horse-power applied in driving a dynamo. This can be measured directly either by using a transmission dynamometer, or by taking an indicator diagram from the steam engine that is driving it, or, in certain special tests where the field-magnets can be pivoted or counterpoised, by applying the method originally pursued by the Rev. F. J. Smith, and later described by M. Marcel Deprez and by Professor Brackett, in which the actual mechanical interaction between the armature and field-magnets is utilized to measure the horse-power used in driving the machine. If, then, we know the mechanical horse-power applied, and if we measure the output of electric horse-power of the dynamo, we have by comparing the mechanical power absorbed with the electric power developed, a measure of the *efficiency* of the dynamo.

The energy per second of a current is expressed as the product of two factors, namely, the number of *amperes* of current, and the number of *volts* of potential between the two ends of that part of circuit in which the energy to be measured is being expended. The number of amperes of current is measured by a suitable amperemeter ; the number of volts of potential by a suitable voltmeter. The product of the volts into the amperes expresses the electric energy expended per second, in terms of the unit of power denominated the *watt.* As 1 horse-power is equal to 746 watts, the number of volt-amperes (*i.e.* of watts) must be divided by 746 to give the result in horse-power. If C represents the current in amperes, and V the difference of potential in volts, then the number of watts of power, for which we may use the symbol w, may be written

$$\text{H P} = w \div 746 = \text{C V} \div 746. \quad . \quad . \quad [\text{V.}]$$

The ratio of the useful electrical power utilised in the external circuit to the total electric power that is developed in the armature is called the "electrical efficiency" or "economic coefficient" of the machine. It may be expressed algebraically as follows :—If through an armature there is flowing a current of C_a amperes, and its total electromotive-force be E volts, then its total electric activity, expressed in watts, will be

$$= \text{E}\,\text{C}_a.$$

If the volts of pressure between the terminals of the dynamo be V, then the useful activity or power utilised is

$$= \text{V C watts.}$$

Using the symbol η_1 for the "economic coefficient," or so-called "electrical efficiency," we have

$$\eta_1 = \frac{\text{useful power}}{\text{total power}} = \frac{V\,C}{E\,C_a},$$

or, if the machine has no shunt, so that C and C_a are the same thing, then

$$\eta_1 = \frac{V}{E}.$$

But we know that the ratio $\frac{V}{E}$ depends on the relation of the internal and external resistances, for

$$\frac{V}{E} = \frac{R}{r + R} \text{ (see equation [III.])},$$

where R is the resistance of the external circuit, and r the internal resistance (armature, series coils, etc.) of the machine. Hence, for a series dynamo or a magneto machine,

$$\eta_1 = \frac{R}{r + R}. \quad \dots\dots \quad \text{[VI.]}$$

Obviously, this coefficient will approach more and more nearly to *unity* the more that the value of r can be diminished. For if a machine could be constructed of *no* internal resistance there would be none of the energy of the current expended in driving the current through the armature and wasted in heating its coils.

We shall see later on how the expression for the economic coefficient η_1 must be modified in the case of shunt dynamos and compound dynamos.

Remembering that the gross electric power of the machine is E C_a watts, or, in horse-power E $C_a \div 746$, we have for η_2 the *gross efficiency*, or efficiency of electric conversion.

$$\eta_2 = \frac{E\,C_a}{HP \times 746},$$

and for the *nett efficiency*, or useful commercial efficiency,

$$\therefore \eta = \eta_1 \times \eta_2 = \frac{V\,C}{HP \times 746}.$$

It will be seen that, as the first of these expressions contains E, and the second V, the nett efficiency can be obtained from the gross efficiency by multiplying by η_1, the economic coefficient.

The *nett or commercial efficiency* may also be expressed by dividing the output V C, by the total of the output plus the sum of all the various losses, electrical and mechanical, reckoned in watts. Or in symbols

$$\eta = \frac{\mathrm{V\,C}}{\mathrm{V\,C} + \Sigma\, w'};$$

where $\Sigma\, w'$ stands for the sum of the losses due to resistance in copper in armature and in the exciting coils, to the hysteresis and eddy-current losses, and to friction and windage. Or, if expressed as a percentage, the efficiency will be

$$\eta = 100\,\frac{\mathrm{V\,C}}{\mathrm{V\,C} + \Sigma\, w'}, \quad . \quad . \quad . \quad [\mathrm{VII.}]$$

Variation of Efficiency with Load.—It must be noticed before passing from this topic that since C, the current, enters into each of the expressions for efficiency as a factor, the efficiency of the dynamo will differ at different loads.

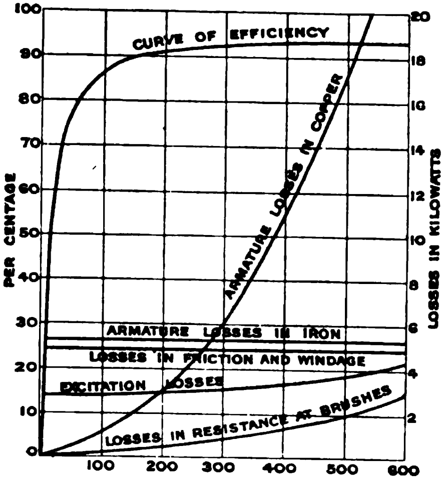


FIG. 169.
TYPICAL CURVE OF EFFICIENCY.

The question at what load a dynamo has its greatest efficiency depends upon its design, and on the proportion of the inevitable losses. Even when a dynamo is giving out no current, there are losses of energy in friction, in heating in the copper of the magnetizing coils, in heating due to hysteresis and eddy-currents in the iron, and to a lesser extent in eddy-currents in moving masses whether of copper or iron. At full load these losses all exist and some of them are increased, but in addition there is the heating in the copper of the armature by the current. As this loss increases with the square of the current while the other losses are nearly constant (at a given speed and voltage), it is clear that at high overloads, the copper heating will become disproportionately great. Consequently the efficiency, which at no-load is zero, goes up to a certain maximum which should be, if the design is good, at the normal maximum load, but which should be high also at half load, and even at one-quarter load; the efficiency curve having in general the form shown in Fig. 169.

THE SERIES DYNAMO.

In the series dynamo (see Fig. 170, also Fig. 43) there is but one circuit, and therefore but one current, whose strength C depends on the electromotive-force E and on the sum of resistances in the circuit. These are:—

R = the external (variable) resistance.
r_a = the resistance of the armature.
r_m = the resistance of the field-magnet coils.

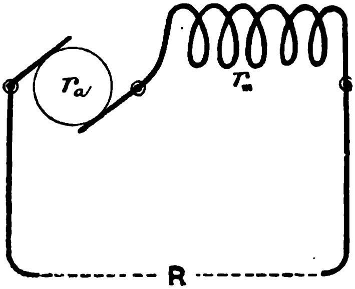


FIG. 170.

By Ohm's law—

$$E = (R + r_a + r_m)\ C.$$

Also V, the difference of potential between the terminals of the machine, is

$$V = C R;$$

whence,

$$V = E - (r_a + r_m)\ C.$$

Economic Coefficient of Series Dynamo.—The economic coefficient η_1, which is the ratio of the useful electric power available in the external circuit to the total electric power developed, will be

$$\eta_1 = \frac{\text{useful power}}{\text{total power}} = \frac{C^2 R}{C^2 (R + r_a + r_m)} = \frac{V}{E},$$

or

$$\eta_1 = \frac{R}{R + r_a + r_m}. \quad . \quad . \quad . \quad . \quad . \quad [\text{VIII.}]$$

This is obviously a maximum when r_a and r_m are *both* very small. They are usually about equal.

THE SHUNT DYNAMO.

In the shunt dynamo, there are two circuits to be considered; the main circuit, and the shunt circuit (Fig. 171, and Fig. 44). The symbols used have the following meanings.

C = the current in the external main circuit.
C_a = the current in the armature.
C_s = the current in the shunt circuit (the lost amperes).

Then, clearly,

$$C_a = C + C_s;$$

because the current generated in the armature divides into these two parts in the main and shunt circuits, and is equal to their sum.

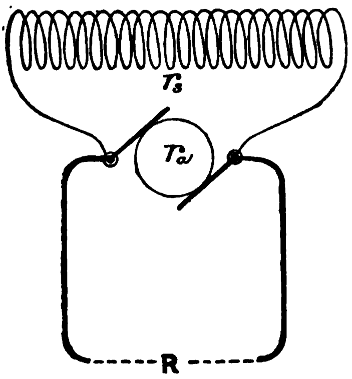


FIG. 171.

We may call that part of the whole current which returns through the shunt, and is not available in the external circuit, the *lost amperes*: in a good modern machine they are at most, from 1 to 2½ per cent. of the whole output of current. If r be the resistance of the shunt coils, the lost amperes may be calculated

$$C_s = V \div r_s.$$

For example, in the Kapp bipolar dynamo, p. 621, giving out 200 *amperes* at a pressure of 105 *volts* at terminals, r_s was 31 ohms, hence the *lost amperes* were 3·4, and total current in armature at full load 203·4 *amperes.*

Also, by Ohm's law, we have for V the electromotive-force between terminals.

$$V = C\,R,$$

and also

$$V = C_s\,r_s;$$

because the terminals for the main circuit are also the terminals for the shunt circuit.

Further, since the nett resistance of a branched circuit is the reciprocal of the sum of the reciprocals of the resistances of its parts, the nett external resistance from terminal to terminal is equal to $\frac{R\,r_s}{R + r_s}$; and hence it follows that

$$E = \left(r_a + \frac{R\,r_s}{R + r_s}\right)C_a.$$

We may at the same time find an expression for e the lost volts, viz. that part of the whole electromotive-force which is being employed solely to overcome the resistance of the armature, and which is, of course, the difference between E the total electromotive-force, and V the voltage between the terminals.

Ohm's law at once gives us

$$e = E - V = r_a\,C_a.$$

From this we also get

$$V = E - r_a(C + C_s). \quad . \quad . \quad . \quad [IX.]$$

We will also find an expression for E in terms of V and the various resistances. Taking as above

$$E = \left(\frac{R\,r_s}{R + r_s} + r_a\right)C_a,$$

and writing for C_a its value as $C + C_s$, and for these V/R and V/r_s respectively, we get

$$E = V\left\{\frac{R r_s + R r_a + r_a r_s}{R + r_s} \times \frac{R + r_s}{R r_s}\right\},$$

or

$$E = V \times r_a\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right).$$

It may be noted that the expression $\left(\frac{1}{R} + \frac{1}{r_a} + \frac{1}{r_s}\right)$ is the sum of three conductances of three paths, and is therefore equal to the conductance of these three paths united in parallel with one another; that is to say, the conductance as measured from brush to brush with the external circuit and shunt circuit joined up. Or, if we write $\mathfrak{R}$ for the resistance of the whole system of machine and circuit, as thus measured from brush to brush, then the equation may be written

$$E = V \times r_a/\mathfrak{R}.$$

EFFICIENCY OF SHUNT DYNAMOS.

A very simple way of regarding the efficiency of shunt dynamos is the following:—

The *gross* watts of the machine $W = E\,C_a$, where E and C_a are both armature quantities: and the *nett* watts actually delivered in the external circuit will be $w = V C$. Now E may be written as equal to $V + \delta V$, where δV represents the lost volts (due to internal resistance), and $C_a = C + \delta C$, where δC represents the amperes wasted in magnetizing in the shunt coils. Substituting we have:

$$W = V C + V \cdot \delta C + C \cdot \delta V + \delta C \cdot \delta V. \qquad [X.]$$

Neglecting the fourth term as being a small quantity of the second order, we may interpret the three terms on the right-hand side as being respectively the nett output of the machine, the watts wasted on excitation, and the watts wasted on internal heating in the copper. Heat losses in the iron and friction losses do not appear here, though they add to the mechanical power needed to drive the machine. Considering then purely the electrical efficiency of the dynamo we see that

$$\eta_1 = \frac{w}{W} = \frac{VC}{VC + V\delta C + C\delta V} \quad . \quad . \quad . \quad [XI.]$$

That this ratio should approach as near to unity as possible it is obvious that $V \,.\, \delta C$ and $C\,\delta V$ should *both* be as low as possible. Writing the loss as a fraction of the output we have

$$\frac{1 - \eta_1}{\eta_1} = \frac{\delta C}{C} + \frac{\delta V}{V}, \quad . \quad . \quad . \quad . \quad [XII.]$$

the two terms being of equal importance. Equating them, and inserting the values of δC and δV in terms of resistance, we have :—

$$\frac{V}{r_s C} = \frac{C r_a}{V};$$

where

$$\frac{V}{C} = \sqrt{r_a r_s}$$

or

$$R = \sqrt{r_a r_s} \,. \quad . \quad . \quad . \quad [XIII.]$$

This is equivalent to saying that to make the two losses in armature heating and shunt magnet heating equal the armature resistance and shunt resistance should be such that the resistance of the external circuit is a geometrical mean between them. Now we may write the equation [XI.] of relative losses as :—

$$\frac{1 - \eta_1}{\eta_1} = \frac{R}{r_s} + \frac{r_a}{R}; \quad . \quad . \quad . \quad [XIV.]$$

from which it is clear that for the percentage of losses to be small r_s must be *large* and r_a *small* compared with R. If, for example, the copper losses of the machine (iron losses and friction not being taken here into account) are not to exceed 4 per cent., and to be equal in armature and shunt, r_s must be fifty times as large as R, and r_a only one-fiftieth of R, so that r_s will be 2500 times as great as r_a.

Examples: *Shunt Machines.*—the values of r_s/r_a are as follows in the following machines: Siemens' dynamo (1880), page 337, 48·4; Edison-Hopkinson Dynamo (1886), page 26, 1702.

Compound-wound Machines.—Including the resistance of the series winding with that of the armature, the values of $r_s \div (r_a + r_m)$ are as follows in the following machines: Kapp bipolar (1887), page 621, 945; Scott and Mountain (1901), page 582, 12,600.

The commercial efficiency is of course lower than the mere electrical efficiency, which does not take into account hysteresis and eddy-current losses, windage, or friction. See Chapter XVII.

CONSTANT POTENTIAL DYNAMOS.

Conditions of Supply.—For some purposes—as for feeding a system of incandescent lamps in parallel—the current must be supplied from the mains at an absolutely *constant potential* or *pressure*; that is to say, the difference of potential between the mains must be constant. This, of course, implies that the current delivered by the machine shall vary exactly in a ratio inverse to that of the resistance of the external circuit; increasing, as the resistance is diminished by adding to the number of lamps across the mains of the circuit. But we have seen that, owing to two causes—(1) internal resistance, (2) demagnetising reactions of armature—the volts at the terminals at full load fall short of the value they would have (at the same speed and magnetization) at zero load. The *pressure-drop* increases with the load. Hence, means must be taken to compensate for the lost volts if the supply is to be maintained *at a constant pressure.* If the dynamo is to supply lamps at, say 100 volts, the pressure must not be allowed to drop to 97 or 96 volts when all the lamps are at work.

For some other purposes, as for supplying a set of lamps connected in a simple series, placed on one line, it is necessary to maintain in the line an absolutely *constant current*, no matter how many or how few lamps or motors may be at work. This, of course, means that when the resistance of the main circuit is increased by the switching-in of more lamps, the dynamo must put forth a proportionate increase of electromotive-force.

The two ends to be attained by regulation are therefore not only distinct, but incompatible with one another; a dynamo cannot possibly keep its electromotive-force constant, and at the same time vary it in proportion to the varying resistance of the external circuit. The two systems are adapted to entirely different cases of electric distribution. Their theory is different; and the practical modes for carrying them out are different also.

Constant-current machines, as required for arc-lighting, and for glow-lamps in series, are described in Chapter XXII. The present section deals only with machines for supply at constant or nearly constant pressure.

There are various ways of governing dynamos so as to maintain either a constant potential or a constant current. Some of these methods involve hand regulation; others, automatic switching in or out of resistance, to vary the excitation of the field-magnets; others, automatic adjustment of the brushes; and others, electrical governing of the speed. Chapter XXVI. on Regulators deals with these. Let it be noted in the first place that the voltage of a given dynamo depends, as shown by the fundamental equation (p. 282), on three factors—the speed, the number of armature-windings, and the magnetic flux: hence it follows that any one of these might be used to control the voltage of the machine. The speed *might* be changed by merely mechanical contrivances. The number of effective armature conductors *might* be reduced by shifting the brushes forward beyond the neutral point. The magnetic flux can be varied by altering the magnetizing force that excites the magnetism, or by changing the disposition of the magnetic circuit.

In cases of isolated plant it may be convenient to apply a governor to so vary the speed in accordance with the demands on the circuit as to maintain a constant electric pressure; but this is not satisfactory when the engine has other work than driving a single dynamo. Hence, methods have been preferred which admit of the maintenance of a constant speed of driving. Throughout this chapter this condition will be assumed to hold good; and as a purely magnetic method of regulation is but little used we need only deal here with the methods that depend on varying the excitation of the magnets.

In central stations and power-houses different methods obtain according to circumstances. For supplying lighting currents to a compact district lying immediately around a central station, some engineers prefer to use simple shunt machines, each operated by its own engine, and to keep up the voltage on each machine simply by opening the stop-valve of the engine at times when the dynamo is heavily loaded. In this case the speed is purposely varied. In supplying the rapidly fluctuating currents to a tramway from a power-house situated necessarily at some distance from the outlying parts, and where the drop of voltage may be considerable and liable to rapid changes, regulation either by the resistance of the shunt or by varying the engine-speed is quite out of the question. A constant speed, within the limits of engine-governing, must be maintained, and regula-

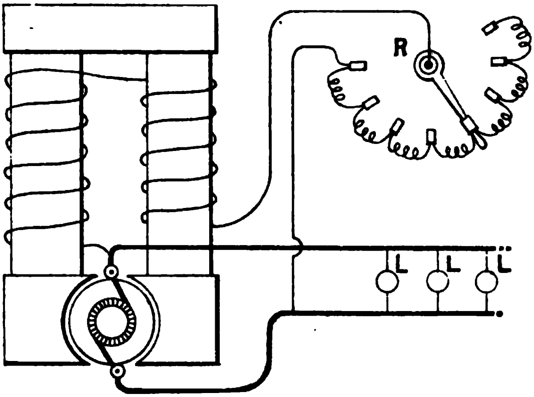


FIG. 172.—EDISON'S METHOD OF REGULATING.

tion effected by over-compounding (see p. 318), or by the use of boosters (see Chapter XXIV.)

Hand Regulator.—Edison introduced a method of supplying mains at a constant potential in which a shunt dynamo is employed : a variable resistance, or rheostat, R, being introduced into the shunt-circuit (Fig. 172). A lever moved by hand, whenever the voltage rises above or drops below its proper value, makes contact on a number of studs connected with a set of resistances, and thus controls the degree of excitation of the field-magnets. Lane-Fox suggested to make the arrangement automatic ; the variable resistance being adjusted by an electro-magnet the coils of which are an independent shunt across the mains. The shunt dynamo, if well constructed, is, as shown on p. 344, nearly constant in its voltage ; the pressure at the terminals falls off very little at full load. With such a dynamo, but a small increase of exciting current is needed to make up for the pressure-drop at full load. The regulating rheostat is equally applicable to a separately excited machine. For further considerations concerning rheostats see Chapter XXVI.

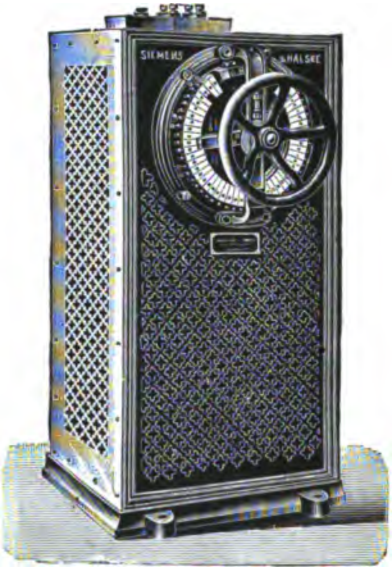


FIG. 173.—REGULATING RHEOSTAT (SIEMENS AND HALSKE).

Self-regulating Machines.—The theory of self-regulation is extremely simple. At full load the volts tend to drop because of the armature reaction and because of internal resistance. Now they depend on the flux ; hence, any drop in the volts can be compensated by increasing the flux. The problem then is how to make the main current, which as it increases causes the volts to drop automatically, increase the flux. It is clear that a compensating main-circuit coil of sufficient turns to produce the needed *additional* excitation, must be wound upon the field-magnet. The compensating coil must obviously be thick enough to carry the main current, and usually consists of few turns. If the machine is shunt-wound to begin with, and a compensating coil in series with the armature is thus added, the combination is usually termed a *compound* winding. A compensating series-coil is, however, equally applicable to any well designed dynamo in which the initial magnetism is independently excited. The following combinations are possible :—

A. *Compound Winding.*

(*i.*) Permanent magnets to excite the field initially with an independent magnetisation + regulating coils in series.

(*ii.*) Separate excitation of the field-magnets from some independent source + regulating coils in series.

(*iii.*) Shunt excitation of the field-magnets supplied by a portion of the current of the machine itself + regulating coils in series.

(*iv.*) Dynamo with two field-magnets surrounding one elongated armature, one field-magnet being excited independently or by a shunt-winding, the other having relatively few turns of thick winding, in series with the armature.

B. *Booster Methods.*

Current in the circuit generated with a constant electromotive-force (either by a battery or by an independent magneto or separately-excited or shunt machine), which current is then passed through a dynamo, having for its excitation a few turns of thick wire in series with its armature driven at a constant speed.

C. *Alternate-current Compounding.*

Alternate current dynamos may be compounded by providing them with regulating coils supplied with a current derived (by a suitable transformer) from the main-circuit current, and proportional to it: the derived currents being first sent through a rectifying commutator. The independent magnetization may be derived either from an auxiliary exciter, or from a separate coil or group of coils in the armature, or, in fact, by another transformer, the primary of which is placed across the mains as a shunt; in either of the latter cases the current being properly commuted. For the newest methods see Vol. II.

Theoretically, several other self-regulating combinations are possible; for example, a series machine with unsaturated magnets, combined with a (quasi-independent) series machine with oversaturated magnets on the same shaft; a series machine having two sets of field-magnet poles at different leads, one of the sets of poles being the series-excited set, the other excited independently, or in shunt circuit, etc. Theoretically also, a shunt-wound or separately-excited machine might be made self-regulating if its brushes were given a *backward* lead. But owing to sparking this is impracticable unless the armature is wound on Sayers' plan (p. 270), with a compensating winding.

THEORY OF SELF-REGULATION.

In considering the theory of self-regulation we shall proceed as follows:—First find an expression for the pressure at the mains. This will, in general, consist of three terms. Secondly, we shall consider these three terms as to whether their factors are constants or variables. Then, having ascertained which of the terms contain variable factors, we must consider what conditions must be laid down (such as prescribing a particular speed or a particular number of windings) in order that the terms containing variable factors shall disappear. These conditions will be embodied in an "equation of condition," which will be then discussed. In general it will be found that if the speed is prescribed beforehand, there will be a certain "critical" number of regulating coils to be deduced; or, on the other hand, if the number of regulating coils is prescribed beforehand, there will be a particular or "critical" speed at which self-regulation holds good.

It is possible to treat the theory either algebraically or geometrically. Both methods will be here used.

Case (i.). Permanent Magnets + Series Regulating Coils (Fig. 174, p. 313).—If the field-magnets are partly permanently magnetized, or if there are permanent steel magnets in addition to the electromagnets, giving an initial field, we may denominate the initial flux as N_1.

Now the fundamental equation of the dynamo is

$$E = n M,$$

and the difference of potential or pressure at the terminals is found by deducting the lost volts; or

$$V = E - (r_a + r_m) C.$$

But M is proportional to N, the number of magnetic lines that pass through the armature at any instant, is made up of two parts, the permanent independent part N_1, and a part depending upon the current C, and equal to

$$\frac{4 \pi S_m C \div 10}{\Sigma \frac{l}{\mu A}};$$

where S_m is the number of turns in the compensating coil, l the length of the magnetic circuit, A its cross-section, and μ the *average* value of the gross permeability (iron and air together) between the two extreme values that it has when C is zero and when C is at its maximum. Hence also we may regard M as made up of two parts, M_1 and a variable part. If for brevity we write

$$\frac{Z}{10^8} \times \frac{4 \pi}{10} \Big/ \Sigma \frac{l}{\mu A} = q,$$

we may then write the variable part of M as $q S_m C$; and therefore

$$M = M_1 + q S_m C;$$

and we get, as the complete expression for V,

$$V = n (M_1 + q S_m C) - (r_a + r_m) C,$$

or

$$V = n M_1 + n q S_m C - (r_a + r_m) C.$$

The expression on the right-hand side of this equation consists of three terms, of which the first contains the speed and two constants as factors. The last two contain a variable, the current, and one of them also contains as factors the speed n and the number of regulating coils S_m. If S_m is prescribed beforehand, then the particular speed at which the dynamo is self-regulating will be clearly that speed at which the expression for V will contain nothing but constants. If n is prescribed beforehand, then we must vary S_m so as to eliminate the terms that contain the variable factor. Since the two last terms are of opposite sign, it is clear that by varying S_m or n, or both, the value of $n\,q\,S_m$ may be made numerically equal to $r_a + r_m$. Then at the constant speed, which we will call n_1, the last two terms will cancel one another out, or,

$$n_1\,q\,S_m\,C - (r_a + r_m)\,C = 0.$$

That is to say, S_m and n_1 must be such that

$$n_1\,q\,S_m = r_a + r_m. \quad . \quad . \quad [\text{XV.}]$$

This is the equation of condition.

If the condition laid down in this equation is observed. then the last two terms for V disappear, and we have simply,

$$V = n_1\,M_1 = \textit{a constant.}$$

Having thus proved that, at the given speed, V is a constant, it is worth while to inquire what it is that determines the value of V. Clearly V is directly proportional to M_1 and therefore to N_1, the initial flux. Therefore, we can arrange that the dynamo still driven at the given speed, shall give any pressure we please, within limits, provided we alter N_1 in the requisite proportion.

Suppose that the speed is prescribed by mechanical considerations, then the proper or critical number of regulating coils is given by the expression

$$S_m = \frac{r_a + r_m}{n\,q}. \quad . \quad . \quad . \quad [\text{XVI.}]$$

This is instructive. The higher the internal resistance of a dynamo the greater must be the number of the regulating coils in series, if it is to be self-regulating.

Returning to the equation of condition, we will write it in the second form—

$$n_1 q S_m = r + r_m,$$

which for a given number of series coils gives us as the value of the critical speed,

$$n_1 = \frac{r_a + r_m}{S_m} \cdot \frac{1}{q},$$

and this speed will be higher the greater the internal resistances are.

Lastly, we may write the last equation in the following way,

$$\text{critical speed} = \frac{\text{total internal resistance}}{\text{number of turns of series coils}} \times \text{a quantity}$$

depending only on the armature windings and on the magnetic circuit and its working permeability within the range for which regulation is required.

So far we have assumed that the only cause of drop of pressure that needed to be compensated for was that due to internal resistances. But the drop of pressure due to the demagnetizing action of the armature is in modern machines a consideration of even more importance. To take account of this action we must remember that if the angle of lead λ is known, the demagnetizing belt of conductors (see p. 261) will be that comprised within an angle of $2\ \lambda$, namely $Z \frac{\lambda}{90^\circ}$. Let the number of paths or circuits through the armature be called c. Each conductor carries $C \div c = C_1$ amperes, making the demagnetizing ampere-turns $Z \lambda C_1 \div 180^\circ$. Or if the number of armature conductors within the angle λ is called D, the demagnetizing ampere-turns will be $2\ D \times C_1$. To compensate this we shall require at least so many series coils that their number, multiplied by the whole current C, shall produce an equal number of ampere-turns, or the number of compensating turns must be *at least* $2\ C_1\ D \div C = 2\ D \div c$. Owing to magnetic leakage some increase is needed, and this may be roughly estimated by multiplying by the coefficient of dispersion v. Hence we shall have to increase S_m, the series coils, from the value found above to the value

$$S_m = \frac{r_a - r_m}{n_1 q} + \frac{2 v D}{c} \quad . \quad [XVII.]$$

In the special case of chord-windings (p. 354), the compensation needed is less than that given by this formula.

Case (ii.) Separately-exciting Coils + Series Dynamo.—In this case there is an initial magnetism due to a separate exciting current.

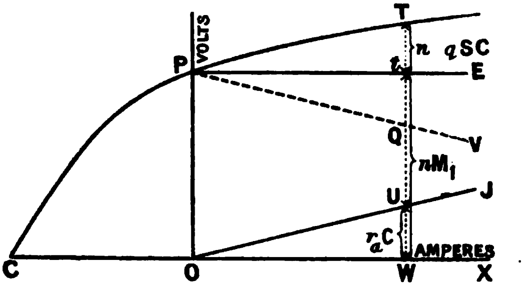


FIG. 174.

If we call the number of magnetic lines due to the independent excitation N_1, the same argument holds good as in the preceding case, and the same conclusions. N_1 will not, however, be really a constant, for the effect of the introduction of a constant amount of magnetizing force will vary with the degree of saturation resulting from the *whole* magnetizing force. If, however, the average working permeability thoughout the range of regulation is taken into account in the calculation of N_1 as well as in that of S, then any falling-off in the effect of the independent exciting current is implicitly provided for.

Geometrical Demonstration of Cases (i) and (ii).—On p. 291 it was shown how the values of the potential at terminals fall off in magneto and separately-excited dynamos as the current increases, e always being less than E by an amount equal to r_a C.

To represent the facts, let O X and O P be taken as the axes for plotting out amperes and volts, and let O P (Fig. 174) represent the electromotive force ($E = n_1 M_1$) due to the permanent or independent magnetism, as measured when no current is running through the armature. Now, assuming that the armature reactions are small enough to be neglected, E will at constant speed remain the same with all currents, but V will drop. From O set off the line O J at an angle such that its tangent represents the internal resistance of the machine. Now consider the case when the current C has the particular value corresponding to the length O W. The height U W will be the drop in the external volts; for U W = tan U O W × O W = r_a C. Cut off from t W a portion, t Q = U W, and Q W will represent V. While the curve for E and C is approximately a horizontal line, the curve for V and C (the external characteristic) falls, as shown by the dotted line. Any point on the V curve can be got from the E curve by simply deducting from the height a piece equal to the corresponding width across the triangle J O X. Now it must be obvious that if when the E curve is horizontal the V curve slopes downward, we must use an E curve that slopes upward by a precisely equal amount, if we want to get a horizontal V curve; that is to say, if we want to get constant potential. How are we to get an upward sloping E curve? Remember that at a given speed, n_1, the value of E is n_1 M_1, where M_1 means that the magnetic circuit has somehow (either permanently or by a separate current) been excited up to the degree requisite at no-load. O P may represent the initial magnetization. Therefore P is a point on a curve of magnetization, which will rise still higher if only we put on more ampere-turns of excitation. Therefore all that is required to be done is to put on the magnets a coil in series, having such a number of turns S_m that the ampere-turns S_m C will have the effect of raising the magnetism in the right proportion; in fact, so that T t shall be equal to U W. We have now got an E curve which slopes up—not quite a straight line, to be sure, but such that when we subtract the volts required to drive the current through the armature resistance, we get a V curve that is appoximately level.

Comparing the algebraic and geometric methods, we see that tV corresponds to n_1 M_1; Tt to $n_1 q$ S_m C; and U W to r_a C, or if the resistance of the added series coil is included in the slope of the line O J, U W will correspond to (r_a + r_m) C.

Case (iii.). Series Regulating Coils + Shunt Exciting Coils: "*Compound Winding.*"—The compound-wound dynamo may be regarded as either a series dynamo to which some shunt windings have been added, so as to provide an initial magnetization, or as a shunt dynamo to which some series windings have been added to compensate for the drop of potential at the terminals. There are two possible methods of connecting the shunt coils to the dynamo, and the proportions differ slightly in the two cases. In the "short-shunt" method the shunt coils are joined as a shunt to the armature part of the dynamo only, being connected across from brush to brush. In the "long-shunt" method the shunt coils are connected across the terminals of the machine, and may, therefore, be regarded either as a shunt to the external circuit, or as a shunt to the armature and series coils together. In the former arrangement the current through the shunt is not constant, because though V may remain fairly constant, the potential at the brushes does not, but increases when the external circuit's resistance decreases. In the latter arrangement the current through the shunt is constant if V is constant, and the case becomes one analogous to those already discussed, of an independent constant excitation. The connexions of the short-shunt method are indicated in Fig. 175. In a well-designed dynamo it makes very little difference whether the shunt is connected across the brushes or across the terminals of the main circuit. The connexions of the long-shunt arrangement are as shown in Fig. 176. The calculations for the two cases are practically identical, and involve the same kind of arguments. That for long-shunt is a little more simple, and is accordingly given.

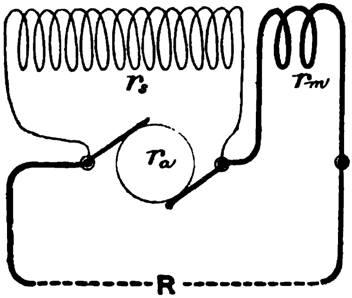


FIG. 175.

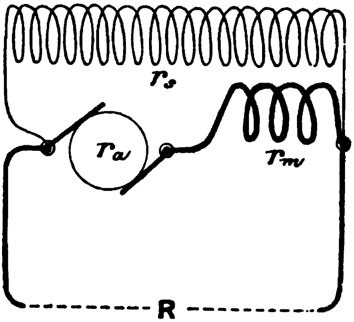


FIG. 176.

We have then

$$E = n M ;$$

$$V = E - (r_a + r_m C_a),$$

and as the magnetism depends on the total number of ampere-turns of excitation we shall write

$$M = q (S_s C_s + S_m C_a) \quad . \quad . \quad [XVIII.]$$

where q has the same signification as before (p. 310), and is the variable number representing, at the various stages of magnetization, the numerical ratio between flux and excitation for the magnetic circuit of the particular dynamo. For the present purpose it is also necessary to consider the value which q has when the external current is zero, and when the only excitation is that due to the shunt : this may be called q_o. Then the initial flux on open circuit will be :—

$$M = q_o S_s C_s.$$

Then from the three equations we have

$$V = n q S_s C_s + n q S_m C_a - (r_a + r_m) C_a.$$

Now here we have three terms, the first containing, as factors, the speed (which may be kept constant), and the shunt current C_s which will be made constant if V can be made constant ; the second contains the speed also as a factor ; the second and third both contain the variable current C_a. The two variable terms are of opposite sign. Now V cannot possibly be a constant, when two of its terms contain a variable as factor, unless the coefficients of that variable factor are such that they make those two terms cancel one another ; V cannot be constant unless either the speed n or the windings S_m, or both, are so adjusted as to fulfil this. But these can be varied. so that it is possible for the two coefficients to be equal, viz.—

$$n q S_m = r_a + r_m.$$

This is then one of the two equations of condition ; and the critical number of series-turns at the given speed will be

$$S_m = \frac{r_a + r_m}{n} \cdot \frac{1}{q}.$$

Or, if S_m is prescribed, the critical speed will be

$$n = \frac{r_a + r_m}{S_m} \cdot \frac{1}{q}.$$

If this condition be observed, then V will be constant and have the value

$$V = n q S_s C_s.$$

But this would leave V indeterminate, since $C_s = V \div r_s$. But we may reflect that though this equation might not give us the value of V, there will nevertheless be a determinate value for it, namely, the same value that V would have when there is no current taken from the dynamo at all, but when it is running on open circuit only. Under these conditions the value of V will be

$$V = n M_o - (r_a + r_m) C;$$

or, since here q has the value q_o,

$$V = n q_o S_s C_s.$$

But $V = C_s r_s$, whence we get

$$n = \frac{r_s}{S_s} \cdot \frac{1}{q_o}.$$

Comparing this value of n with that obtained in the first equation of condition, we get

$$\frac{r_s}{S_s q_o} = \frac{r_a + r_m}{S_m q};$$

whence, finally, as the *second* equation of condition,

$$\frac{S_s}{S_m} = \frac{r_s}{r_a + r_m} \cdot \frac{q}{q_o}.$$

As q_o is proportional to μ_o the initial permeability when the shunt only is at work, and q proportional to the average permeability μ for the range of working between zero current and maximum current, it follows that if there were no alteration of saturation, $q \div q_o$ would equal 1.

To compensate for the demagnetizing action of the armature, additional turns are required in the series coil, as explained above on p. 312. To make the last set of formulæ complete S should be replaced by $S - \frac{2 v D}{c}$.

Over-compounding.—It will be noticed that, apart from the demagnetizing action of the armature, the amount of excitation to be provided for by the series coils is always proportional to the resistances that are in the main circuit and *internal to the point for which the constant difference of potential is desired*; this renders it possible, in a case where the mains leading from a dynamo to the lamps are long, so to compound the dynamo by adding more coils in series as to give a constant potential, not at its terminals, but at the distant point of the circuit where the lamps are to be used. This is a most valuable circumstance in all cases where the lamps are far from the dynamo, as in the lighting of mines from machinery at the surface, or as in the case of long feeder mains; for then by *over-compounding*, one can obtain a constant pressure, not at the terminals of the dynamo, but on the mains at some feeding-point in the distributing network. There is another advantage in over-compounding, namely, that when the full load comes upon a machine, the engine, however carefully governed, generally slows down a little, tending to produce a further drop in the voltage. As an example of over-compounding it may be mentioned that the 6-pole street-tramway generator, described on p. 677, required about 4000 ampere-turns per pole on open circuit, but had a series-winding which allowed an additional 6000 ampere-turns per pole at full load.

Arrangements of Compound Winding.—Compound windings may be arranged in several different ways. If wound on the same core the shunt coils are sometimes wound outside the series coils: more frequently the series coils are outside the shunt. In the former editions of this work the recommendation was made to wind the series coils nearer the pole than the shunt coils. If the magnetic circuit through the ironwork be good, the position of the coils makes little difference.

Predetermination of Compound Winding.—The predetermination of the amount of compound winding as a part of practical designing depends (1) on the preliminary estimation of the amount to which the voltage must be raised at full load ; (2) on an estimation of the demagnetizing reactions to be compensated. Directions for taking these into account are to be found in Chapter XVII., and examples of working out are given in Chapter XIX. in the analysis of some typical machines.

A Practical Process for Compounding.—Let the armature of the machine be run at the proper speed dictated by mechanical considerations, and let a voltmeter be applied at the terminals. Two experiments are then necessary. First, by means of temporary coils, having a known number of turns wound on the field-magnets, and furnished with measured currents from some accumulators or another dynamo, ascertain the number of ampere-turns that will suffice to excite up the magnets to this point. From this Z can be determined ; for C_s is known beforehand, say 2 per cent. of the whole current at full load. Secondly, put into the main circuit some resistance to represent the maximum load of lamps, and while the machine is running at its proper speed, ascertain, using still the temporary coil and accumulators, how many ampere-turns of excitation are needed in total when the machine is doing full work. Subtract from this the value of $C_s S_s$ obtained in the first experiment, and the remainder gives the number of ampere-turns which the series coil must furnish ; and as the maximum current is known, S_m can at once be calculated. The same process suits for over-compounding, the excitation at full load being raised until the volts at terminals rise to the higher number of volts that will allow for the drop in the leads.

Adjusting Shunt.—Some makers of compound dynamos adopt the practice of providing their machines with a series-winding of a higher number of turns than is actually needed for giving the prescribed voltage at full load, and adding to this winding an *external shunt* which can be adjusted after the machine is installed ; this shunt being a mere by-pass which reduces to any required extent the ampere turns of additional excitation. If iron is used for this external shunt, then owing to the high temperature coefficient of its resistance, it will when hot carry a less fraction of the whole current, thus causing the voltage to rise still higher at full load.

Balancing Wires. — Where two or more compound machines are to be operated in parallel, it is necessary to provide an extra terminal to enable a balancing wire to be carried between the machines in order that they may be put in parallel, not only on external circuit but also at the brushes, so as to equalize the voltages at their armatures. The reader should consult the passage on coupling dynamos in Chapter XXVII.

CHAPTER XII.

CHARACTERISTIC CURVES.

MANY practical problems in the construction of dynamo-electric machines are in the present state of science solved by the use of graphic diagrams, and particularly by the use of certain curves technically called *characteristics*. The method of constructing and using these curves forms an important part of the theory of the dynamo. The characteristic curve stands indeed to the dynamo in a relation very similar to that in which the indicator diagram stands to the steam engine. As the mechanical engineer, by looking at the indicator diagram of a steam engine, can at once form an idea of the qualities of the engine, so the electrical engineer, by looking at the characteristic of the dynamo can judge of the qualities and performance of the dynamo. The comparison may even be said to reach farther than this.

The steam-engine indicator diagram serves two purposes which, though not unconnected with one another, are yet distinct. When the scale on which the diagram is drawn is known, it gives direct information as to the horse-power at which the engine is working, depending on the total area enclosed by the curve, and quite irrespective of its form. But even though the actual scale be not known, the details of the form of the curve at its various points give very definite information to the engineer as to the working of the engine, the perfection of the exhaust, the setting of the valves, the efficiency of the cut-off, and the adequacy of the supply pipes and port-holes of the valves.

So also the characteristic curve of the dynamo may serve two functions. When the scale on which it is drawn is known it tells the horse-power at which the dynamo works; nay, can indicate at what horse-power the dynamo may be worked to the greatest profit. But even though the actual scale be not known, the details of the form of the curve afford definite information as to the conditions of the working of the machine; the degree of saturation of its magnets, the sufficiency of the

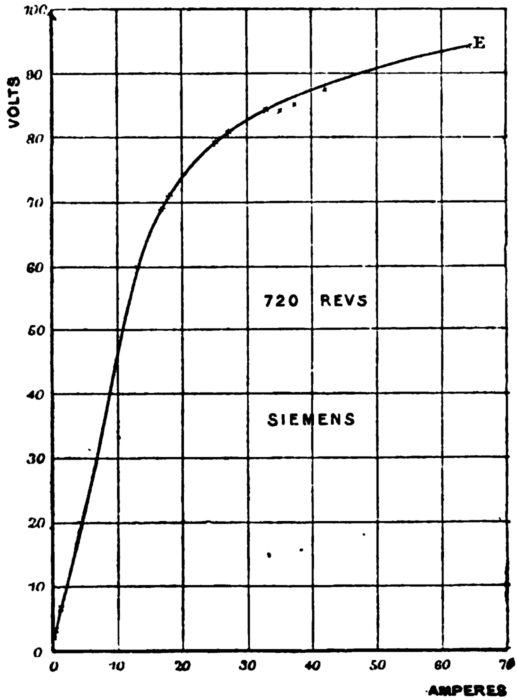


FIG. 177.—CHARACTERISTIC CURVE OF A SERIES DYNAMO.

field-magnets in proportion to the armature, and the goodness of the design in several respects.

The first self-exciting dynamos put into commerce were *series* wound; they were found to possess a most puzzling instability of behaviour, sometimes losing their current altogether, and refusing to excite themselves. This and other peculiarities were not understood until the curves of their performance were studied.

The suggestion to represent the properties of a dynamo machine by means of the characteristic curve is due to the late Dr. John Hopkinson, who in 1879 described such curves to the Institution of Mechanical Engineers, and gave the curve of the Siemens dynamo reproduced in Fig. 177. The name of "characteristic" was assigned in 1881 by M. Marcel Deprez[1] to Hopkinson's curves; and the excellence of the name has been attested by its general adoption.

EXPERIMENTS ON SIEMENS DYNAMO AT SPEED OF 720 REVOLUTIONS PER MINUTE.

Current (in amperes). C	Resistance (in ohms). R	Electromotive-Force (in volts). E
0·0027	1025	2·72
0·48	8·3	3·95
1·45	5·33	7·73
16·8	4·07	68·4
18·2	3·88	70·6
24·8	3·205	79·5
26·8	3·025	81·1
32·2	2·62	84·4
34·5	2·43	83·8
37·1	2·28	84·6
42·0	2·08	87·4

Hopkinson's object was to represent the relation subsisting between the electromotive-force and the current; he therefore constructed from observations a curve in which the abscissæ measured horizontally represent the number of amperes of current flowing, and the vertical ordinates the corresponding values of the electromotive-force. The table above gives the observed values C of the current, and E the electromotive-force, of a certain series-wound dynamo.

It may be remarked that the electromotive-force E is the total electromotive-force generated in the machine, and must not be confounded with V the difference of potential between the terminals as measured by a voltmeter, or other similar instrument. In many cases we now prefer to plot V instead of E; but that was not Hopkinson's original method. He determined E by measuring C and multiplying it by the total resistance of the circuit; for by Ohm's law C R = E. It should also be remarked that the dynamo was a "series dynamo," shunt-wound machines not having at that date come into vogue.

---

[1] Vide *La Lumière Électrique*, Dec. 3, 1881; where, however, Deprez gives a method of observation that is open to the objection that it neglects the armature reactions.

Before entering into other points, it may be worth while to consider the meaning of the curve. It begins at a point a little above the origin. This shows that there was a small amount of residual magnetism remaining permanently in the field-magnets. The curve ascends at first at a steep angle, then curves round and eventually assumes a nearly straight course, but at a gentler slope than before. As the speed is constant the only variable of importance is the magnetism. As this rises and grows toward a maximum, so does the induced electromotive-force. We might therefore expect that this curve should exhibit peculiarities of form similar to those of the curve which represents the relation between the magnetizing current and the magnetization of an electromagnet; and a comparison of Fig. 177, the "characteristic" of the series dynamo, with Fig. 51*a*, the "magnetization curve" of an electromagnet, will suffice to reveal the analogy. It must, however, be remembered that the magnetism of the dynamo is affected by the reaction of the armature.

Dr. Hopkinson, in the paper alluded to, and in a second one published in the *Proc. Inst. Mech. Engin.*, in April 1880, p. 206, pointed out a great many of the useful deductions to be drawn from a consideration of these curves. Some other deductions have been made by M. Marcel Deprez, for which the reader is referred to *La Lumière Électrique*, of Jan. 5th, 1884. Dr. O. Frölich also published several important papers on the subject in the *Elektrotechnische Zeitschrift* for 1881 and 1885. Hopkinson returned to the subject in a lecture before the Institution of Civil Engineers, "On Some Points in Electric Lighting," April 1882. See also his book on *Dynamo-Electric. Machines* (London 1893), and the Reprint (Cambridge 1901) of his *Original Papers*, vol. i. pp. 32 to 132.

As mentioned at the beginning of this chapter, if the characteristic curves are drawn to scale the output of the dynamo may be read off from them in horse-power. The unit of electric power, the product of one volt into one ampere, has been called by the special name of one *watt*. One watt is equal to $\frac{1}{746}$ of a horse-power. To calculate the horse-power (electrical) evolved in the circuit when the dynamo is running with any number of lamps in circuit, two measurements have ordinarily to be made—the volts of electromotive-force and the amperes of current. These must then be multiplied together and divided by 746 to obtain the horse-power. But if the characteristic of the dynamo at the particular speed be known, a reference to the curve will show at once what the electromotive-force is that corresponds to any particular current. For example, in the Siemens dynamo examined by Hopkinson, the characteristic of which is given in Fig. 177, p. 322, suppose the dynamo was working through such a resistance as to give 30 amperes when running at 720 revolutions, we see at once that the corresponding electromotive-force is 83. Hence

$$\frac{83 \times 30}{746} = 3 \cdot 3 \text{ horse-power.}$$

Now to obviate such calculations we may plot out on the diagram some additional curves crossing the characteristics and mapping them out into equal values of horse-power. These "horse-power lines" are nothing else than a set of rectangular hyperbolas. For example, the 1-horse-power line will pass through all the points for which the product of volts and amperes is equal to 746. It will therefore pass through the point corresponding to 74·6 volts and 10 amperes; through 37·3 volts and 20 amperes; through 14·92 volts and 50 amperes, etc., because the product in each of those cases is equal to 746 watts or 1 horse-power. The 2-horse-power line will pass through points whose product values are equal to

46 × 2; the other lines are drawn similarly. Fig. 178 shows the characteristic of the Siemens machine, reproduced from Fig. 177 above, but with the horse-power lines added.

In this case the volts plotted are the total electromotive-force E, of the dynamo, and therefore the horse-power represents the gross electric output. If instead of E we had plotted the values of V, the volts at the terminals, we should have had a slightly different curve, representing the nett output available for useful purposes in the external circuit.

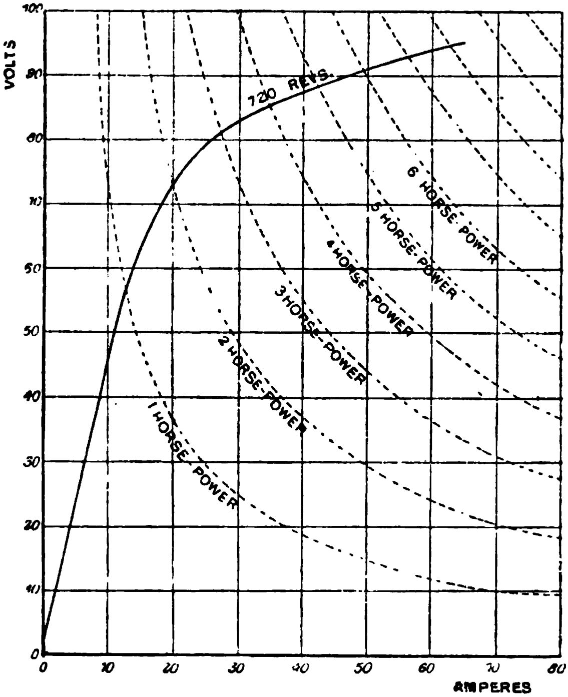


FIG. 178.—CHARACTERISTIC WITH HORSE-POWER LINES.

If the vertical and horizontal scales are not chosen equal, the horse-power lines, though hyperbolæ, are of course distorted.

External Characteristics or Terminal Potential Curves.—The name *external characteristic* may be given for the sake of distinction to those curves which exhibit the relation between the potentials and the currents of the external circuit. In the series dynamo it is a simple matter to derive one of these curves from the other, provided the internal resistance of the machine (armature and field-magnets) is known. In the Siemens dynamo examined by Hopkinson in 1879, and of which Figs. 177 and 178 give the total characteristic, the total internal resistance was 0·6 ohm. The curve is reproduced for

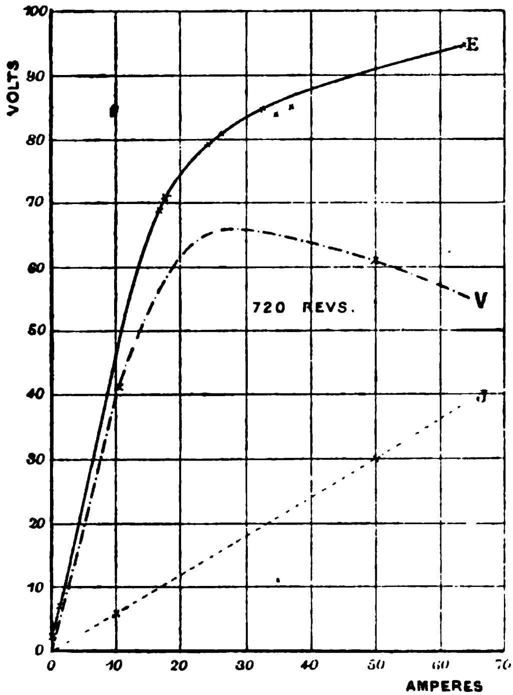


FIG. 179.—TOTAL AND EXTERNAL CHARACTERISTICS.

a third time in Fig. 179, where it is marked "E." Now to force a current of 10 amperes through a resistance of 0·6 of an ohm would require a difference of potential of 6 volts between its terminals. Looking at the curve we see that the whole electromotive-force, corresponding to 10 amperes, was about 46·5 volts. Of this number, 6 were employed as mentioned, in overcoming the internal resistance, leaving 40·5 volts as the available potential between terminals. Further, when the current was running at 50 amperes, there must have been no less than 30 volts *lost* in overcoming the internal resistance of 0·6 ohm: and as the value of E for this current is 90·5 volts, there remain 60·5 volts for V. There are now two ways open to us of representing these matters on our diagram. They are both shown in Fig. 179. The line J is drawn through the origin, and through the values of 6 volts for 10 amperes and 30 volts for 50 amperes. (The tangent of the slope of the line J is equal to $6 \div 10 = 0{\cdot}6$. We shall see later that this slope represents the internal resistance.) Then if the heights of the ordinates from the base line up to the line E represent total volts induced, and if the heights of the ordinates from the base line up to the line J represent the corresponding volts lost in overcoming internal resistance, it follows that *the difference of potentials at the terminals will be represented by the differences of the ordinates between the lines* J *and* E. This is the first way of representing those differences of potentials. The second way is to cut off from the tops of the ordinates portions equal to those of the line J. This amounts to subtracting the internal volts, which, as shown in the algebraic theory are equal to $C\,(r_a + r_m)$, from E, and so obtaining the values of V. These are plotted out in the curve marked "V" in the figure; and as this curve represents the available electromotive-force in the external circuit, it obtains the name of *external characteristic* or terminal potential curve. As a matter of fact it is more usual to reverse the operation. The terminal potential values are easily observed with a voltmeter and the current with an ampere-meter. Then the external curve for V and C is plotted; and by *adding* to the ordinates the corresponding values of the lost volts, and so obtaining the curve for E and C. If there is permanent magnetism in the magnets, the characteristics will not start from the origin, but from a point a little above it.

Characteristics of Series Dynamo.—The Siemens dynamo of which the characteristic is given in Fig. 177, was a series dynamo. For the sake of comparison the characteristic is given in Fig. 180 of an "A" Gramme machine also series-wound. This machine had, when it was measured by M. Marcel Deprez, 0·41 ohm resistance in the armature coils and 0·61 ohm in the coils of the field-magnets. Two characteristics are given; one corresponding to a speed of 1440, the other to a speed of 950 revolutions per minute. The horse-power lines are also shown dotted.

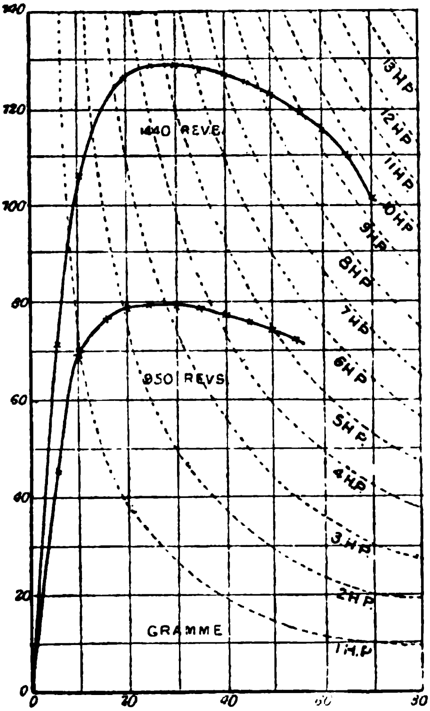


FIG. 180.—CHARACTERISTIC AT DIFFERENT SPEEDS.

In the series dynamo the magnetization of the magnets increases with the current, and therefore, at first, the electromotive-force increases also, giving the first straight portion of the curve. As the magnets approach saturation the curve turns, and, as the reactions due to the current in the armature now become of relatively great importance, flattens itself and ultimately turns down again; the increased lead of the brushes greatly adding to the effect because it increases the demagnetizing reaction of the armature. The dip in the characteristic is always greater in the case of weak field-magnets, or of those machines that are far from saturation in the teeth and pole-tips.

For the special purpose of studying the magnetization of the machine it is convenient to mark the abscissæ in *ampere-turns* rather than in *amperes* only.

One more curve of a series-wound dynamo is given in Fig. 181. This is a small Brush machine (intended to supply a single arc light) of the early pattern, with solid iron ring, in which, owing to the peculiar arrangement of the coils (see p. 737), the reactions of the armature make themselves known by a very extraordinary down-bending of the characteristic. This is partly due to the arrangements for cutting out a pair of coils as they approach the neutral point. It will be noticed that the maximum horse-power of this small machine is 1¾ horse; and that this value is only obtained when the reactions have already set in. This diminution in the electromotive-force is in practice a real advantage. Should the machine be accidentally short-circuited while running, the reactions of the armature prevent the production of an injuriously large current, which might overheat the coils. It is an advantage in machines for arc-lighting, where a nearly constant current is required, to employ machines with drooping characteristics, and to work them at this part of the curve (see p. 750).

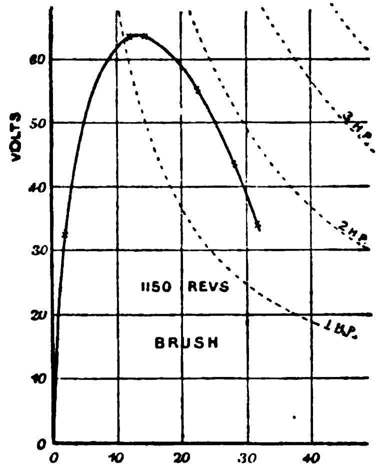


FIG. 181.
DROOPING CHARACTERISTIC.

Relation of Characteristic to Speed.—The electromotive-force generated in a rotating coil or armature would be strictly proportional to the field, were it not for the reactions of the armature. Now in a series dynamo, the field depends on the current; and, if the current is kept constant (by adjusting the resistances), the field will also be constant even though the speed be varied. If therefore the characteristic of a machine be known at any speed, its characteristic for any other speed can be found by the very simple process of increasing the ordinates of the curve in a similar proportion. Take, for example, the case of the Gramme dynamo, of which a characteristic at the speed of 250 revolutions is given in Fig. 180. The characteristic at 1440 could be calculated from it by increasing the ordinates in the proportion of $\frac{1440}{950}$. Thus we see from the lower curve that when the current was 20 amperes the electromotive-force was 79 volts. Then $79 \times 1440 \div 950 = 119{\cdot}7$ volts. The actual electromotive-force observed at the speed 1440 and with current at 20 amperes was 127 volts. There is a slight discrepancy here, and indeed always; for series machines behave invariably as if a certain number of the revolutions did not count electrically. If the number of "dead turns" (see p. 217) were here reckoned as 140, the number of volts calculated by theory would agree very exactly with that observed.

Resistance in the Characteristic.—In the characteristic we have volts plotted vertically and amperes horizontally. Now by Ohm's law, volts divided by amperes give ohms. How can this be represented in the characteristic? Suppose, for example, it is required to represent the resistance of the circuit corresponding to some particular current. Let Fig. 182 be the characteristic of the dynamo in question, and it is desired to know what is the resistance corresponding to the state of things at the point marked P. Draw the vertical ordinate P M, and join P to the origin O. The line P O has a certain slope, and the angle of its slope is P O M. Now P M is equal to the electromotive-force under consideration, and O M is the current. Therefore, by Ohm's law,

$$\text{Resistance} = \frac{\text{electromotive-force}}{\text{current}} = \frac{\text{P M}}{\text{O M}};$$

but

$$\frac{\mathrm{P\,M}}{\mathrm{O\,M}} = \tan \mathrm{P\,O\,M}\,;$$

therefore the resistance = tan P O M. Put into words, this is :—*The resistance corresponding to any point on the characteristic by the trigonometrical tangent of the angle made by joining the point to the origin.* An easy way of reckoning these tangents is shown in Fig. 182. At the point on the horizontal line corresponding to 10 amperes erect a vertical line. A line drawn from the origin at an angle whose tangent is = 1 (namely 45°) would cross this vertical line at a point opposite the 10-volt mark. This point may then be called 1 ohm, and equal distances measured off on this line will constitute it a scale of resistances. In Fig. 182 the resistance corresponding to point P of the characteristic is seen to be about 1·2 ohm on the scale of resistances. Now P is placed at 51·3 volts, and the current is 43·2 amperes. Dividing one by the other, we get 1·18 ohm. Such calculations are then obviated by the graphic construction.

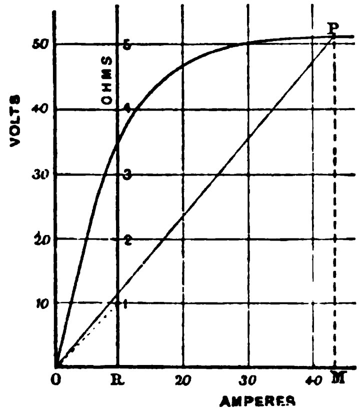


FIG. 182.—METHOD OF REPRESENTING RESISTANCE GRAPHICALLY.

If in the actual dynamo the resistance of the circuit were gradually increased, we should have the point P displaced along the curve backwards towards the origin, the volts and amperes both falling off, and the steepness of the line O P increasing. When O P arrived at a certain steepness it would practically form a tangent to that part of the characteristic which is nearly straight, and then any very small increase in the resistance would cause the dynamo to lose its magnetism, from lack of current to magnetize the magnets.

Resistance may be similarly represented on the characteristics of any dynamo ; but if the characteristic is drawn for the *external* current and the *external* difference of potential, then the resistance so represented will be the *external* resistance.

Relation of Characteristic to Winding of Armature and Field-Magnets.—Suppose the armature of a machine to be rewound with a larger number of turns of proportionally thinner wire. What will be the result at the same speed as before? The resistance will be increased somewhat, and the electromotive-force also will be higher. Let Fig. 183 represent the characteristic of the machine as it was when there were Z conductors of wire on the armature. How must it be drawn when the number is increased to Z′? Let P represent a point corresponding to a certain strength of current. Taking the new armature, let the external resistance be varied until the current once more comes to the same value. The magnets are now magnetised exactly as strongly as before; but there are Z′ conductors of wire cutting the magnetic flux, instead of Z. The electromotive-force will therefore also be greater in the like proportion. Draw therefore P′ C so as to have the proportion P′ C : P C : : Z′ : Z. All other points on the new characteristic can be obtained by similarly enlarging the ordinates in the same ratio.

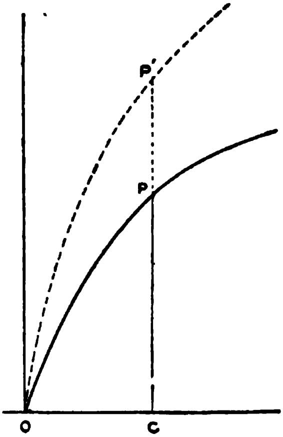


FIG. 183.

It will be evident from this that increasing the number of turns of wire in the armature has the same effect as increasing the speed of driving. This shows that *slow speed* dynamos (for use on ships, or as exciters) may be made to give the requisite electromotive-force provided the number of turns of wire be relatively increased. This involves, however, a sacrifice either of efficiency, because of the increase of resistance in the armature, or else of prime cost if thicker wire is used.

The effect of altering the number of turns of wire on the field-magnets can also be traced out on the characteristic diagram. Suppose the number of turns in the magnetizing coil be S, and that we re-design the machine, increasing the number to S′ turns. What will the result be? In this case we shall get the same electromotive-force when driving at the same speed as before, provided the magnets be equally magnetized. But if the current goes S′ times round instead of S we shall want a current only S/S′ as strong as before, to produce the same magnetization. To get the new characteristic then (see Fig. 184), draw P E horizontally. P E = C O = the current corresponding to electromotive-force E. Find P′ such that P′ F : P E : . S : S′; then the new characteristic will pass through P′. Similarly, all other points of the new characteristic may be determined by reducing their abscissæ in a similar proportion.

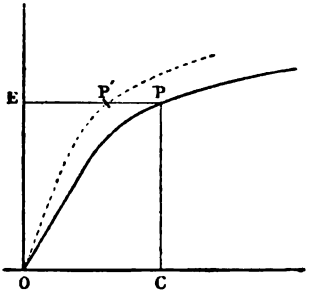


FIG. 184.

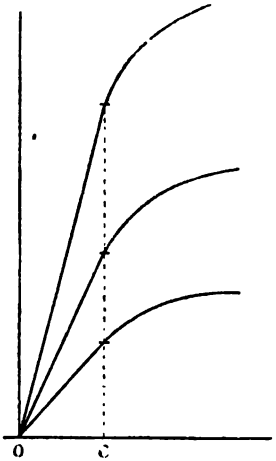


FIG. 185.

It must be noted that the latter process is not admissible for the characteristics of shunt-wound machines.

If keeping the resistance constant the speed is increased, the increase of current can be found by reference to Fig. 186. Let the dynamo be at first working at the point P. The resistance of the circuit is the slope of the line O P. Now draw the new characteristic for the higher speed by increasing the ordinates proportionally. Let the point where the new characteristic crosses the line O P be called P′. The abscissa O C′ corresponding to P′ gives the relative value of the current.

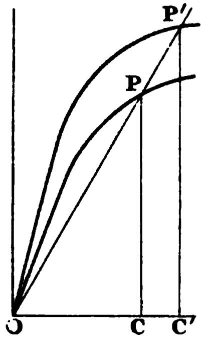


FIG. 186.

Critical Current of Series Dynamo.—From the fact that the characteristics for different speeds differ only in the relative scale of the ordinates, an important consequence may be deduced. The first part of every characteristic for any speed is nearly straight up to a point where for that speed the electromotive-force is nearly two-thirds of its maximum value. When the current is such that the electromotive-force has attained to this value, any very small change either in the speed of the engine or in the resistance of the circuit produces a great change in the electromotive-force, and therefore in the current; therefore since this critical case occurs always with the same current (see Fig. 185), this current—corresponding to the point on all the curves where the straight line begins to turn—may be called the "critical current" of the dynamo. This is the explanation of the puzzling instability remarked on p. 332. The series dynamo only "builds" its magnetism when the resistance is low enough, and when excited and running will "unbuild," or lose its magnetism, if the resistance of the circuit is increased too much. Each series dynamo has its own critical current, and it will not work with a less one; for a less one will not adequately excite the field-magnets. Since with each speed the characteristic rises with a corresponding slope, there will be at each value of the speed one particular resistance at which the current will have the critical value; and the higher the speed the higher may be the resistance. There is no such thing as a critical resistance *per se*: for whether a resistance is critical or not depends upon the speed. *Neither is there any such thing* per se *as a critical speed for a series dynamo*; for whether the speed is critical or not, depends on the resistance of the circuit.

Characteristic of Magneto Machine, and of Separately-excited Dynamo.—In the magneto machines the magnetism of the steel magnets is approximately constant. So would the magnetism be in the iron of separately-excited machines if the exciting current is kept constant, provided the cross-magnetizing and demagnetizing tendency of the currents in the armature coils were absent. But the stronger the current in the armature, the stronger these reactions. And, as explained on p. 260, the demagnetizing tendency increases with the lead given to the brushes.

A careful study of the characteristics of separately-excited dynamos was made by Mr. W. B. Esson, who gave the following curve for a separately-excited dynamo having a modified Pacinotti ring armature. The line E (Fig. 187) represents the total electromotive-force if there were no reactions. The line V represents the values of the potential between the brushes of the machine as it would be if there were no reaction.

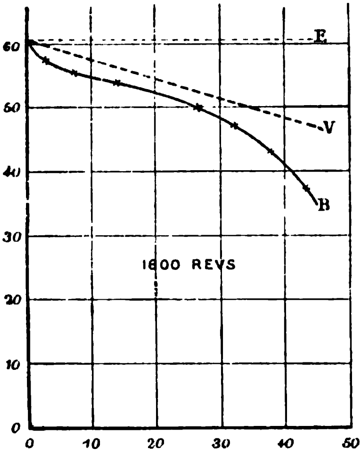


FIG. 187.—CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

The curved line B gives the actually observed values of V when different currents were taken from the machine. The greater drop at the lower end of the curve is probably due to the greater demagnetizing effect when there is a considerable lead at the brushes. The characteristic always shows such downward curvature more when the field-magnets are weakly excited.

CHARACTERISTIC OF SHUNT DYNAMO.

For the shunt dynamo there are two separate characteristics; the *external characteristic*, in which the quantities plotted are the amperes of current in the external circuit and the volts of potential between terminals ; and the *internal characteristic* in which the volts and amperes of the shunt circuit are plotted. The internal characteristic of the shunt dynamo is quite similar to the external characteristic of a series dynamo, and shows the saturation of the field-magnets. It is better to

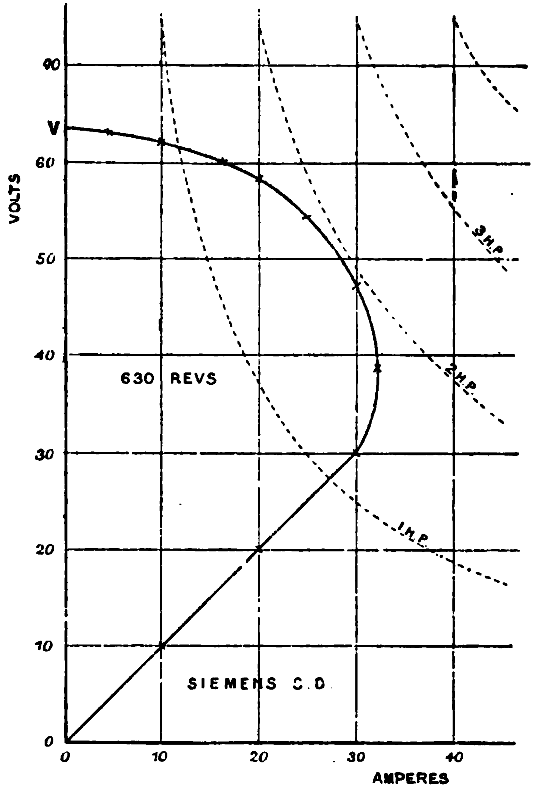


FIG. 188.—EXTERNAL CHARACTERISTIC OF SHUNT DYNAMO.

plot it with amperes-turns instead of amperes, because the magnetization depends on the number of turns in the coil as well as the amperes.

The external characteristic of a small shunt dynamo (the same described by the late Sir William Siemens before the Royal Society in 1880, and by Mr. Alexander Siemens in the *Journ. Soc. Teleg. Eng.*, March 1880) is given in Fig. 188, and the horse-power lines are shown dotted. The utmost power of this machine at 630 revolutions was just under 2 horse-power with a current of 30 amperes, and an electromotive-force of 47·5 volts.

The curve of the shunt dynamo is curiously different from that of the series dynamo. It begins, on open circuit, at a point (marked V), where the volts are a maximum, and runs slightly descending from the horizontal : then descends rapidly and returns toward the origin in a nearly straight line. The straight portion represents the unstable state when the shunt current is less than its true critical value. The critical external current, if it can be so called, is in Fig. 188 about 30 amperes. The slope of the line which constitutes the last portion of the characteristic represents the resistance which for the particular speed may be termed the critical resistance, and in this case is about 1 ohm. Any less resistance will cause the magnets to lose their magnetism at once. Any

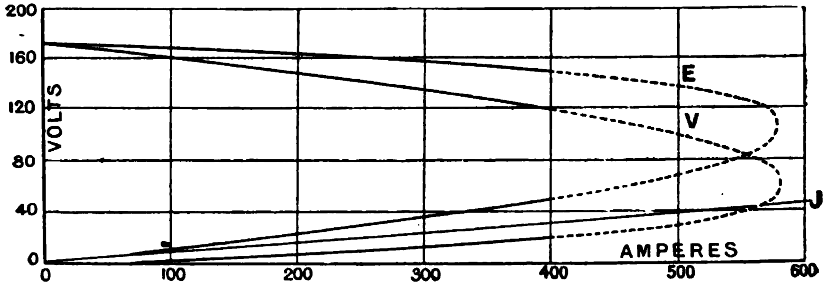


Fig. 189.—Characteristic of a Shunt Dynamo.

greater resistance will at once run the electromotive-force up above the critical value—in this case about 30 or 31 volts. If the resistance of the external circuit becomes in the least degree altered, the electromotive-force and current will alter enormously. If the resistance be steadily increased (and the slope of the line from O to the curve be increased in steepness) the volts will go on steadily augmenting, and become a maximum when the external resistance is infinite, that is to say when a circuit is completely opened and the shunt coils receive the whole of the electromotive-force of the armature. Fig. 189 depicts the characteristic of a shunt-wound Gramme dynamo capable of giving 400 amperes. In this case the curve V represents the external characteristic, from which the curve E is calculated by adding to the ordinates portions equal to r_a C_a. As the conductors of the armature could not safely carry more than 400 amperes, the dotted portion of the curve represents results not actually observed. It is instructive to contrast the characteristic of the shunt dynamo with that of a series dynamo (Fig. 177). In the series dynamo, the first part of the characteristic is a sloping line, and the tangent of the angle of its slope is also the critical resistance for the given speed. But the series dynamo will only work if the resistance of the external circuit is *less* than the critical value, and the shunt dynamo will only work if the external resistance is *greater* than the critical value. The contrast is even better shown by drawing a couple of curves in the two cases — not characteristics — showing the relation between the potential at terminals and the resistances of the external circuit. Fig. 190 shows this for a series machine, and Fig. 191 for a shunt machine. The electromotive-force of the one drops suddenly when the resistance exceeds 2 ohms; that of the other rises suddenly when the resistance attains the value of 1 ohm.

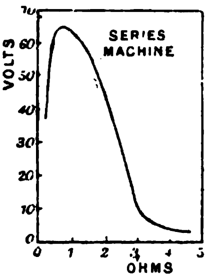


FIG. 190.

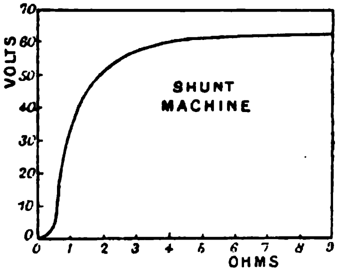


FIG. 191.

In the shunt dynamo the characteristic for a double speed cannot be obtained as in a series dynamo by doubling the heights of the ordinates, unless we adjust resistances so that we get the same shunt current as before. This is shown in Fig. 192, where V *a* represents the external current in the first case, and the slope of the line O_a is the resistance. If this remains unchanged, then if the new characteristic be drawn, the point A where it cuts the line O_a gives the new state of things.

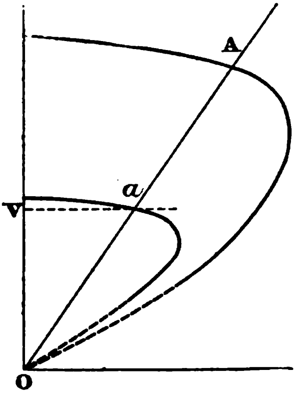


FIG. 192.

Curve of Total Current in Armature.—In the shunt dynamo the current in the armature is equal to the sum of the currents in the external circuit and in the shunt circuit; or

$$C_a = C + C_s.$$

A curve showing the relation between C and V is easily obtained. In Fig. 193 let the curve O *m i* be the "external characteristic" at the given speed. Take any point on it *m*; at that point the potential between terminals in volts is measured

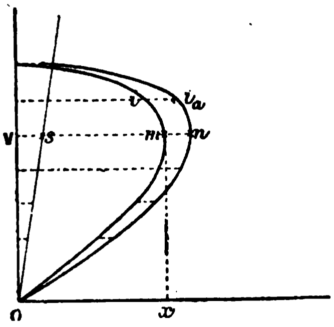


FIG. 193.

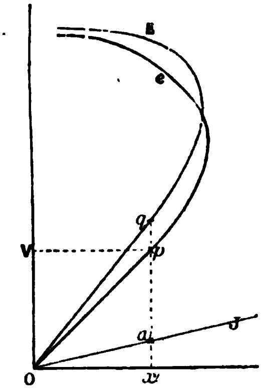


FIG. 194.

by the length of *m x* or O V, and the current in amperes is measured by the length O *x* or V *m*. Now draw the line *s* O at such an angle *s* O *x* that its tangent is equal to the resistance of the shunt. Then V *s* represents the current that will run through the shunt when the potential is O V volts.

Add on to the end of V m a piece $m\,n$ equal to $e\,s$; then the whole line V n represents the armature current C_a when the potential has the value O V. A set of similar points may be found giving the new curve O $n\,i_a$ required.

Total Characteristic of Shunt Dynamo.—If the total electromotive-force E and the total current C_a be plotted out we shall obtain the characteristic of the total electrical activity of the dynamo. This is done in Fig. 194.

Draw, as in the preceding case, the curve for V and C_a. Let p be any point on the curve where the potential is $p\,x$ or O V and the current Vp or Ox. Then draw a line O J at such an angle a O x that its tangent is equal to the resistance of the armature. Call the point where this cuts $p\,x$, a. Then $a\,x$ represents the number of volts required to drive the current O x through the armature resistance. Add a piece $q\,p$ equal to $a\,x$ to the summit of the line $p\,x$. Then the height $q\,x$ represents the total electromotive-force E when the current C_a has the value represented by O x.

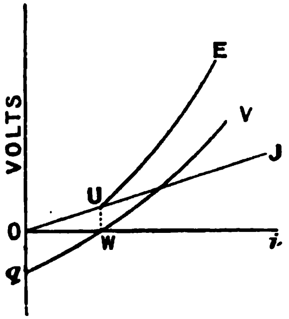


FIG. 195.

Characteristic of Shunt Dynamo, with Permanent Magnetism.—If there is residual magnetism in the field-magnets, there will be an electromotive-force induced, even before the shunt-circuit is closed. In this case the characteristic would begin at a point W, a short distance along the horizontal axis. In fact the machine behaves as though there were already at work some small electromotive-force (not to be plotted), which had the effect of setting up already a current through the machine, so that the machine excites itself up with currents that are, in the early (and unstable) stages of the magnetization, proportional to the ampere-turns going round the shunt circuit, *plus* some imaginary ampere-turns causing the permanent magnetism. If there is on the field-magnet a second coil, by which an independent magnetization can be introduced, the same kind of result will follow: the characteristic will begin at some point, such as W, the electromotive-force due to the ampere-turns in the shunt being plotted out above O, whilst the length O q below represents the part of the electromotive-force due to the ampere-turns (real or imaginary) of the independent magnetism; and O W represents the current which the machine will give when short-circuited.

There will, in fact, be four curves for a shunt dynamo, namely, those in which the quantities plotted out are respectively V and C; V and C_a; E and C; E and C_a. Of these the first is the *external characteristic*, and the fourth the *total characteristic.*

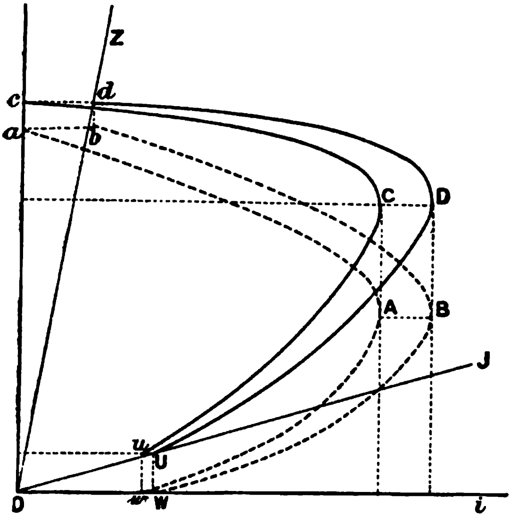


FIG. 196.—FOUR CURVES OF A SHUNT DYNAMO.

These four are depicted in Fig. 196, where they are named A, B, C and D respectively. If D is given, A can be obtained in the following way:—Let the lines O J and O Z represent respectively by their slope the resistance of the armature and of the shunt circuit. The curve B is got from D by deducting from the ordinates lengths equal to the portions of ordinates intercepted by the line O J; and curve C is got from curve D by deducting from the abscissæ lengths equal to the portion of the abscissæ intercepted by the line O Z. Then curve A is got by taking ordinates from B and abscissæ from C corresponding to any point on D.

It may be noticed that whilst D B represents the lost volts due to internal resistance of armature, C D represents the lost amperes which go round the field-magnets. The lower the resistance of the armature, and the higher the resistance of the shunt, the less will these losses be. In fact, with a well-built modern machine the four curves lie very close together.

If the curve of magnetization of the machine is known, it is easy to determine the characteristic by a geometrical construction. The curve of magnetization O P M (Fig. 197) will show the relation between N and the ampere-turns in the shunt coil, $S_s C_s$ in our notation.

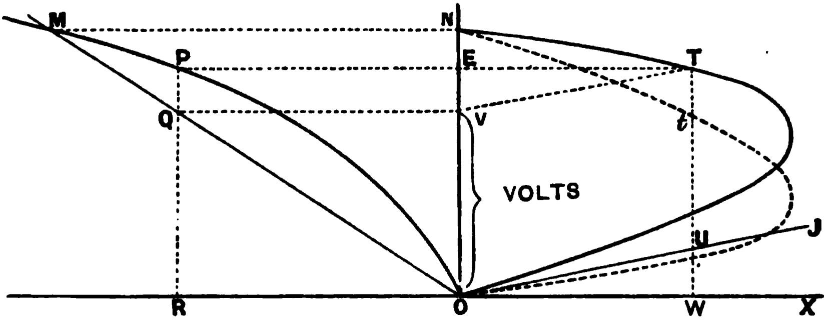


FIG. 197.

Let this curve be set out to the left of the vertical axis, then the line O R may be divided out either in a scale representing *ampere-turns* or in a scale representing *amperes*; S_s divisions of the former scale corresponding to one of the latter scale. The vertical scale plotted out along O E may in like manner represent either N or E; $n \, C \times 10^{-8}$ being the ratio of the readings of the scales. Now set out the line O M, making with O R an angle such that the tangent of its slope corresponds, in the units chosen, to the resistance per turn of the shunt-winding; for example, if the shunt resistance be 16, the line will pass through a point the ordinate of which represents 16 volts and the abscissa 1 ampere. Let this line meet the curve of magnetization at M. If we consider any point P on the curve, its ordinate P R will represent, according as we please, either the effective magnetism when the magnetizing current is O R, or the whole number of volts E induced in the armature; and the part of the ordinate Q R will represent the difference of potential V. Clearly then P Q will represent E − V, that is to say, the volts lost in the armature, which are equal to $r_a C_a$. Now, if on the right of the diagram we lay out a line O J at such an angle that the tangent of its slope represents the armature resistance r_a, then if W be taken so far along the horizontal axis that W U = P Q, the length O V will represent C_a. The most convenient construction is to project points P and Q across to E and V, and from V draw V T, parallel to O U, meeting E T in T; then drop a perpendicular from T giving the points *t*, U and W, where T *t* = U W. T will be a point on the curve connecting E and C_a; *t* a point on the curve connecting V and C_a. From the latter curve the external characteristic can be got as shown on p. 339. Of these hyperbolic curves the lower limb which returns towards O represents the unstable portion corresponding to the lower part of the magnetic curve. From the existence in the curves of a maximum value of C_a, where the curve turns round on the extreme right, it must not be inferred that the machine can yield this maximum current; on the contrary, the maximum current that the machine can safely give depends on the section of its armature wires, and these are—in the best machines—not intended to carry the current under such conditions. The working part of the curve is usually the top part (Fig. 189), and it will be obvious from the construction that the smaller the internal resistance, the further will the curve extend to the right and the more nearly horizontal will the tops of both curves be; a good shunt-dynamo, with very little internal resistance, being *nearly* self-regulating for constant potential.

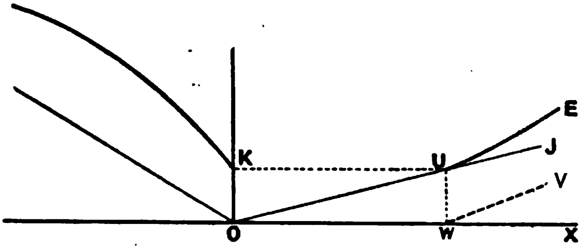


FIG. 198.

If there be no initial or residual magnetization, the curves will both pass through O; but neither of them will do so if there is initial or residual magnetization. In that case the curve of magnetization will commence above O at some point such as K, Fig. 198, and the lower ends of the two curves for E and V will end at points so far to the right that the width U W = K O. With almost every shunt dynamo it is found that if descending values of V are taken (at any given speed) V becomes zero, whilst C has still a definite value.

It will also be noticed that the limiting value of V depends on the slope of M O, that is to say, on the resistance per turn of the shunt coil; any diminution of the resistance per turn will raise E by forcing up to a higher degree the magnetization corresponding to a given value of V.

Series Dynamo Contrasted with Shunt Dynamo.—The difference between series dynamos and shunt dynamos in their behaviour when the resistance of the circuit is increased or decreased, has already been touched upon in p. 339. In electric lighting, dynamos are usually required either (*a*) to supply glow-lamps arranged in parallel, in which case the dynamos must maintain a constant potential at the mains, or else (*b*) to supply arc-lamps arranged in series, in which case the dynamo is required to yield a constant current. In the case where the potential is to be constant, the current will vary with the number of lamps in parallel; in the second case, where the current is to be constant, the electromotive-force must vary as the number of lamps in series.

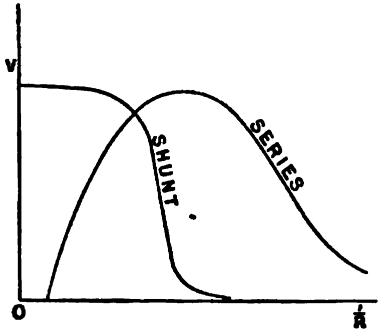


FIG. 199.

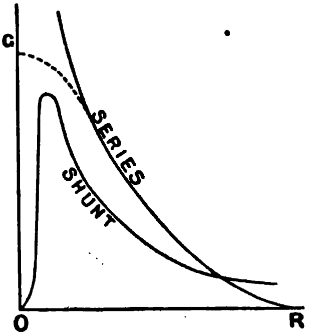


FIG. 200.

To understand the applicability of series or shunt dynamos to either of these tasks, it will be convenient to construct (either from experiment or from theory) comparative curves. In the case of parallel distribution, every additional lamp switched on across the mains adds to the conductance of the circuit an amount equal to its own conductance (*i.e.* equal to the reciprocal of its own resistance). It is therefore expedient to plot out together the values of V and of

$\frac{1}{R}$. This has been done in Fig. 199 for two dynamos, for each of which the maximum value of V was the same. It will be seen that for neither a series nor for a shunt machine does the value of V remain constant as the number of lamps across the mains is increased. The shunt machine gives the more nearly constant potential, but falls off as the number of lamps is increased.

In the case of single-circuit distribution to lamps in series, every additional lamp adds to the resistance of the circuit, and in this case it is expedient to plot out together the values of C and R. Fig. 200 shows the result for the two kinds of machine. It will be seen that neither machine gives anything like a constant current; but for the shunt machine there is just one brief stage, namely, when its current is at the maximum, where the value is more constant than anything that the series dynamo can give. The dotted part of the curve corresponds to the case of a series dynamo so designed as to have a drooping characteristic (like Fig. 181, p. 330), which gives more nearly (with moderately small resistances) a constant current. But it is abundantly clear that something more than a simple series or simple shunt machine is requisite to give a real self-regulating machine for either purpose.

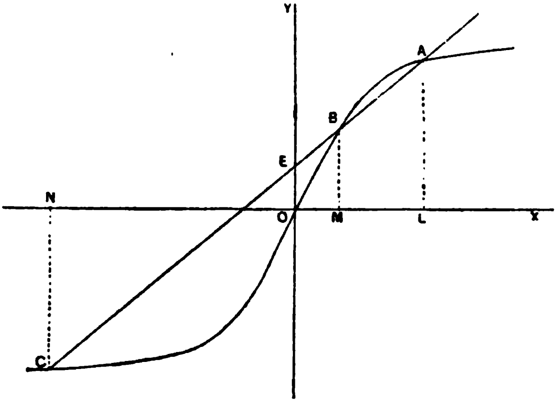


FIG. 201.

Application of Characteristics to Dynamos used in Charging Accumulators.—The following problem is of great practical importance :—*Suppose a dynamo is used for charging an accumulator, and is driven at a given speed, what current will pass through it?*

Hopkinson gave a solution of this problem for the case of a series dynamo. Draw the total characteristic of the dynamo (Fig. 201) for the given speed. Along O Y set off O E to represent the electromotive-force of the accumulator, and through E draw the line C E A, making an angle with O X such that its tangent represents the resistance of the whole circuit, including the accumulators. This line will cut the characteristic in the points B and A; and, if the characteristic be repeated backwards, in C also. This negative branch of the characteristic is simply the characteristic of the dynamo when the current through it is reversed, and its electromotive-force therefore also inverted. Then O L represents the actual current in the circuit; O M represents an unstable current which might exist for a moment; and O N represents the current which would traverse the circuit were the accumulators to overpower the dynamo and reverse it, as indeed frequently happens when series dynamos are so used. For it will be observed that if, as is the case when accumulators are reaching their full charge, their electromotive-force were to rise, or the resistance of the circuit to increase in consequence of heating, the inevitable result would be to diminish A L, the effective electromotive-force, and to diminish the current O L, so that the magnetism of the field-magnets will also drop, and the point A will be brought nearer to the position of instability at the bow of the curve. In that event, though the machine still runs in the same direction as before, it is in reality *motoring*; the current from the discharging accumulators operating to drive it.

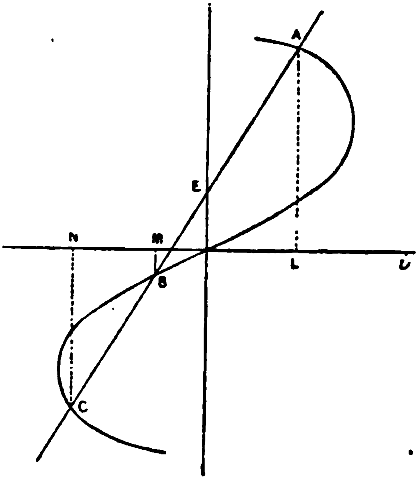


FIG. 202.

With the shunt dynamo the case is different. Let Fig. 202 represent the characteristic of the shunt dynamo, the external current being plotted along O X, and the total electromotive-force along O Y. Draw the line C E A as before. Then it cuts the positive branch at A, and O L is the current in the main circuit. If, now, either the counter electromotive-force of the accumulators or the resistance of the circuit increases, the effect will be to move the point A to a higher point on the curve. The charging current O L may diminish, but the shunt current will increase or the effective electromotive-force A L will be increased. Therefore with the shunt dynamo there will be no likelihood of the accumulators overpowering and reversing the dynamo.

In the case of a series dynamo driving an arc lamp, Fig. 201 also may be applied to explain the instability sometimes observed. The arc acts as though it had a counter electromotive-force, which, for steady arcs is not less than 35 volts. Hence if O E is set off to this value, the resistance of the rest of the circuit must be low enough for the sloping line E A to cut the curve above the "knee," otherwise the condition becomes unstable.

Characteristic of Compound Dynamo.—In the original theory of constant potential machines devised by Marcel Deprez, the argument was based upon the absence of saturation, and the presence of an initial independent magnetization. The following was the argument of Deprez. If there is a permanent excitation of magnetism quite independent of that due to the main circuit coils of the dynamo, the characteristic (Fig. 203) will not start from O, but from some point above it depending upon the amount of independent magnetization and on the speed. Let the starting-point be P. O P is the voltage between the terminals when the main circuit is open, but there is no external current until the circuit is closed, and then the characteristic rises in the usual fashion from P to Q. Draw O J at the proper slope to represent the resistance of the armature and series coils together. Now consider a line O E drawn at such an angle that the tangent of its slope represents the total resistance of the circuit at any particular moment. Then E x is the total electromotive-force at that moment, and a part of this, equal to $a\,x$, will be employed in driving the current O x through the resistance of armature and series coils. The remaining part E a represents the difference of potentials between the terminals of the external circuit. So the problem resolves itself into this: how to arrange matters so that E a shall always be of the same length as O P, no matter how much or how little the line O E may slope. Clearly the only way to do this is so to arrange the speed of the dynamo that the part from P to Q shall be parallel to O J. Then, as shown in Fig. 204, the potential between the terminals will be constant. It will be seen that this agrees with the deductions arrived at in the algebraic treatment of the question: namely, that the critical speed is proportional to the internal resistance; and that the constant difference of potential E a is equal to that due to the independent magnetization O P at the critical speed.

It should also be noticed that if the part of the characteristic be not straight, that is to say, if the field-magnet cores are becoming saturated, the regulation cannot be perfect. If the line P Q be curved, then the potential for large currents will not be equal to that for small currents. If, in the practical process for winding the magnets, the coils have been wound so as to make V the requisite number of volts, both on open circuit (*i.e.* at O P), and at another point (say at Q J), when the dynamo is feeding its maximum load, then there will in general be a slightly greater potential for intermediate loads, owing to the slight convexity of the curve between P and Q.

The above argument holds good whether the independent excitation be due to permanent magnetism or to a combination with separately-exciting coils (see pp. 67 and 69), or to shunt-exciting coils. In the latter case O P represents the potential at terminals due to shunt circuit alone.

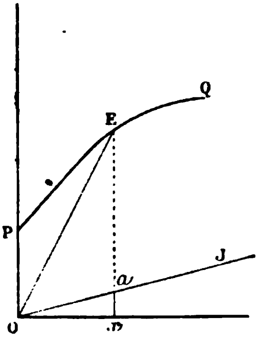


FIG. 203.

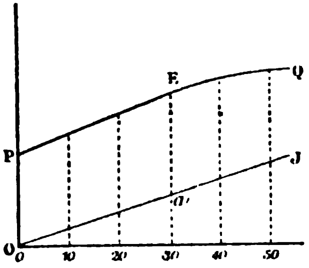


FIG. 204.

External Characteristics of Self-Regulating Dynamos.—Simultaneous observations of the external current C and the external potential V enable us to plot the external characteristic; which in a perfectly self-regulating dynamo would be a horizontal line. If the number of regulating coils in series is too small, the characteristic will fall as the current rises. If too large, it will rise as the current rises; the machine being in that case *over-compounded.* Examples of the performance of compounded dynamos are given in Fig. 384, p. 523, and Fig. 398, p. 594. This latter case, however, is not always a disadvantage, for with machines worked singly on an engine the speed often rises in consequence of imperfect governing when the load on the dynamo is small.

CHAPTER XIII.

THE THEORY OF ARMATURE WINDING.

THIS chapter is devoted to the theory of the ways of joining up and combining the conductors on the armatures of dynamos. Workshop details concerning modes of construction are considered in Chapter XIV.

It has been pointed out, on p. 52, that continuous-current dynamos are usually provided with closed-coil armatures, that is to say armatures on which, whether wound according to the ring, drum, or disk type, the winding is re-entrant on itself, the current dividing between at least two paths and reuniting as it leaves the armature. For machines with two poles there are usually but two such paths, the current dividing once only. But for multipolar machines there may be either two, or more than two, such paths. The electromotive-force of the machine will obviously depend on the mode of connexion of the conductors as to how many active conductors are connected in series. Hence the necessity of understanding the theory of armature winding.

To connect up rightly the conductors on an armature so as to produce the desired result is a simple matter in the case of ring-winding, for continuous-current machines, whether of bipolar or multipolar type. It is a less easy matter in the case of drum-winding, especially for multipolar machines. Often there are several alternative ways of arriving at the same result; and the fact that methods which are electrically equivalent may be geometrically and mechanically different makes it desirable to have a systematic method of treating the subject.

In Chapter III. pp. 50 to 56, we have already considered the elementary structure of ring, drum and disk armatures.

Those elements would suffice for the consideration of small armature coils with only a few turns of wire. But when we proceed to the design of large machines, or of machines which are to be wound so as to give potentials as high as 100 or more volts, further information is needed. For example, suppose we have designed a 4-pole machine having a bar-armature with 100 bars spaced around its periphery, all in one layer, numbered consecutively from 1 to 100, and we desire to complete the end-connexions; we must be able to instruct the workman as to the order in which they are to be connected. Is he to connect the front[1] end of bar No. 1 right across to bar No. 50, or No. 49? Or is he to connect it across a quarter of the periphery, and, if so, is it to join No. 25 or No. 24, or to No. 75 or No. 76? To which return-bar is he to connect the back end of the bar? And which bars are to be connected down to the commutator?

The object of the present chapter is to give information on these points. Brevity is essential; and much more might have been written. Those who wish to go further should consult the writings of Hering,[2] Arnoux,[3] Fritsche,[4] Weymouth,[5] Arnold,[6] Parshall and Hobart,[7] as well as sundry specifications to which reference will be made.

Right and Left-Handed Windings.—As remarked above, there is generally little trouble in understanding a ring winding, provided the distinction between a right-handed and a left-handed winding is comprehended.

---

[1] "Front" end means the end where the commutator is; armatures being always most conveniently regarded from this end.

[2] Hering: *Principles of Dynamo-Electric Machines*, New York, 1891.

[3] Arnoux: *L'Électricien*, xii. 1888, 737, 774, 827.

[4] Fritsche: *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

[5] Weymouth: *Drum Armatures and Commutators*, London, 1893.

[6] Arnold: *Die Ankerwickelung der Dynamomaschinen*, Berlin, 1891. Latest edition, 1899, is entitled *Die Ankerwickelungen und Ankerkonstructionen der Gleichstrom Dynamomaschinen*. Professor Arnold's newest work, *Die Gleichstrommachine*, 1902, handles the theory of windings still more fully.

[7] Parshall and Hobart: *Armature Windings of Electric Machines*, New York, 1895.

Other important articles on this subject are:—

Wiener: *Dynamo Electric Machines* (2nd edition, 1902), p. 143.

Reithofer, Eichberg, and Kallir in the *Zeitschrift für Elektrotechnik*, 1898, p. 17; and Robertson, in the *Journal of the Institution of Electrical Engineers*, 1902, xxxi. 933.

Fig. 205 shows one section of a ring, the direction of the currents being indicated in the same way as on p. 210, Figs. 114 to 116. As we pass right-handedly around the circle from *a* to *b* we follow a right-handed spiral path, the current climbing (as explained on p. 199) to the positive brush at the top. (A left-handed coiling, such as Fig. 33, p. 51, would give the positive brush at the bottom, unless either the rotation or the polarity of the dynamo were reversed.) To say whether a drum armature is right-handedly or left-handedly wound we must first settle upon the particular end of it from the point of view of which our statement is to be applicable; for instance, the commutator end is conveniently taken as the one at which we are supposed to be looking. And we must also fix upon a certain sense of rotation (say clockwise) in which we intend to take the order of the commutator bars. These two matters being fixed arbitrarily, then a right-handed winding may be defined as follows. That winding is right-handed which in leading from one bar to the next (in the order fixed as above) forms a right-handed screw.

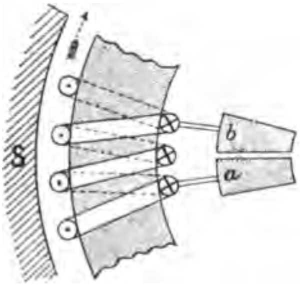


FIG. 205.—RIGHT-HANDED RING-WINDING.

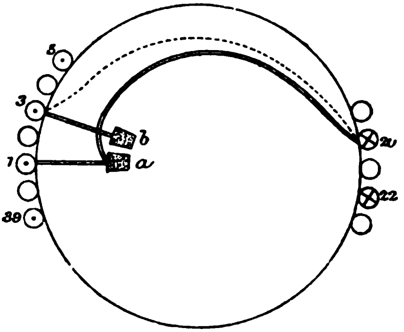


FIG. 206.—RIGHT-HANDED DRUM-WINDING.

Now consider Fig. 206, which depicts one element or section of a drum-winding having 40 external conductors. Starting from *a* to climb to *b*, and noting the direction of the currents in the conductors, it is obvious that *a* must be connected by a spiral connector across the front end of the drum to one of the descending conductors such as No. 20, from which at the back end another connector must join it to one of the ascending conductors, such as No. 3, where it is led to *b*, thus making one right-handed turn. Now examine Fig. 233, p. 388, and Fig. 235, p. 390. The latter is left-handed, each section consisting of one single loop. Note in passing that if the back connector in Fig. 206 from No. 20 to No. 3 had passed under the shaft, instead of over it, the winding would still have been a right-handed winding.

Spacing of Conductors; Pitch of Winding.—The next point is to ascertain over how many conductors these spiral connectors ought to pass. We connected No. 1 (*via* the bar *a*) to No. 20, and then back to No. 3. Is there any reason why No. 20 should have been chosen and not No. 21, or No. 19, or No. 18? To understand this we must consider the question of commutation in the conductors as a whole, and also remember that there are two paths through the windings from brush to brush. This is a drum with 40 conductors in one layer: and there will be 20 bars in the commutator. Remember that the induced electromotive-forces will be directed from back to front in the conductors rising on the left, and from front to back in those descending on the right. It is natural to think that each conductor ought to be joined to the one that lies diametrically opposite to it. In that case No. 1 should be joined to No. 21, No. 2 to No. 22, and so forth. But this will not do. Each conductor on one side needs a return conductor on the other side. The even numbers may be looked upon as the returns for the odd numbers. Hence No. 1 ought not to be joined to No. 21. Shall it be joined to No. 20 or to No. 22? or shall we join it to No. 18? Nos. 20 and 22 lie on either side of the one that is diametrically opposite, and electrically it makes no difference which we select of these two. If we are going to use a back connector which returns over the shaft (as in Fig. 206), there is a slight saving of copper if we select No. 20. If the back connector returns under the shaft, either may be taken. More copper will be saved if we select No. 18 and return over the shaft, as the spiral connectors will be shorter. But if we thus connect across a short chord of the circumference, instead of taking the chord nearest to the diameter, we risk getting counter electromotive-forces in the turns that are in series from brush to brush. On the other hand, as Swinburne has shown, connecting across a short chord has the advantage that the armature has a smaller demagnetizing action. The effect of winding across a chord subtending the span of the pole-piece is shown by Fig. 207, in which it will be seen the belt of demagnetizing conductors between the pole tips is now replaced by a belt, in which the currents flow in two opposing directions, thus neutralizing one another. In no case should the chord subtend a less angle than that subtended by the polar face. The rule then for connecting is as follows for a simple 2-pole drum armature. The number of conductors Z being an even number, the front connector must cross from any conductor to that which is ½ Z ± 1 further on (or ½ Z ± 3 for shortening the chord); and the back connector must lead back to the next conductor but one.

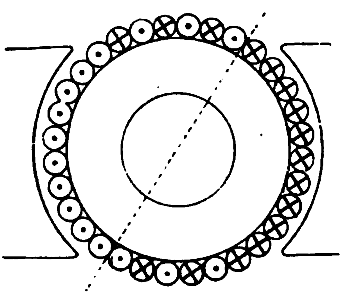


Fig. 207.—Effect of Chord-Winding.

Winding Tables.—Instructions to the winders how to connect the conductors of an armature are sometimes given in the form of drawings, sometimes in the form of *Winding Tables.* Winding tables are also useful in showing how the arrangement of any particular winding works out as to re-entrancy, etc. In the following winding-table the letters F and B stand for *front* and *back*, and the letters U and D stand for *up* and *down*, meaning toward the front end, and from the front end respectively. From this it will be seen that starting with conductor No. 1, we follow *down* it to the back, there connect it to No. 22, then come *up* to the *front*, then come (connecting to a bar of the commutator in passing) to No. 3, go down this and connect across the back to No. 24, and so on. The over-

WINDING-TABLE, 2-POLE DRUM. 40 CONDUCTORS.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
1	22	3	24	5	26	7	28	
9	30	11	32	13	34	15	36	
17	38	19	40	21	2	23	4	
25	6	27	8	29	10	31	12	
33	14	35	16	37	18	39	20	

lap is in this case + 21 at the back end, and – 19 at the front end. At last we come to No. 20, up which we return to the front and connect to No. 1, taking the last bar of the commutator on the way.

Simple as the matter may seem, the problem how to connect across the end of the drum from one conductor to that which is next but one, or next but three, to the diametrically opposite conductor, is not altogether easy when the mechanical and electrical difficulties are taken into account. To shorten the length of the long spiral connectors, and make the end connectors more symmetrical, the arrangements indicated in Fig. 208 is now often used. The spirals are thus arranged in two layers one over the other, as in Fig. 307, p. 446, with the effect that the commutator has virtually been

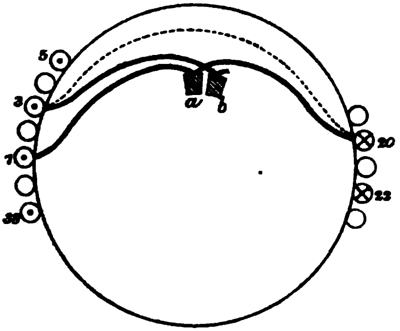


FIG. 208.—DRUM WINDING WITH TWO SETS OF SPIRAL CONNECTORS.

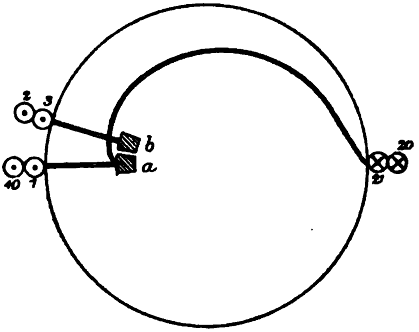


FIG. 209.—TWO-LAYER DRUM WINDING.

turned through about a quadrant, so that the + brush will be on the left instead of at the top. It has the advantage that all the spiral connectors at either end may be made of same size.

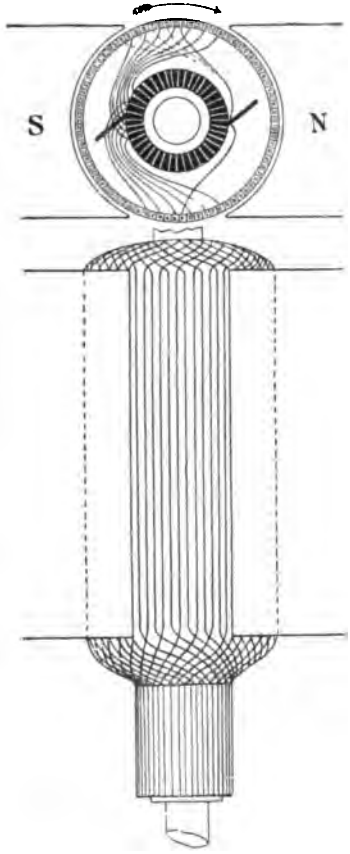


FIG. 210.—DRUM WINDING OF EDISON-HOPKINSON DYNAMO.

If, however, the conductors are arranged in two layers one over the other, the windings may be made across a diameter, the last turn being brought across to the next in the same layer. The conductors of the outer layer then answer instead of the intermediate members of the one layer set. In Fig. 209 the end of No. 1 is brought to *a*, thence it spirals round to No. 21, which is connected across the back to No. 3, and so on. Fig. 210 shows how the 80 conductors of the wire-bound Edison-Hopkinson armature (see p. 26) are connected, there being in reality two layers of 40 each, and a 40-part commutator.

Developed Winding Diagrams.—There is a great advantage in adopting a mode of representation (originally suggested by Fritsche, of Berlin) in which the armature winding is considered as though the entire structure had been developed out on a flat surface.

Consider first Fig. 211, which is a partial sketch of a four-pole machine laid on its side. The core, which may be hereafter wound either as ring or as drum, lies between the four poles of alternate polarity. If a copper rod *a* is placed parallel to the axis to represent one of the armature conductors, and is supposed to move along the gap-space right-handedly past the S pole, it will cut the magnetic lines entering that pole. By the rule given on p. 37, the induced electromotive-force in it will be upwards. Another conductor *c* passing the N pole will have induced it in a downward electromotive-force. If one were to attempt in a picture such as this to show twenty or more conductors and their respective connections, the drawing would be unintelligible. Accordingly we have to imagine ourselves placed at the centre, and the panorama of the four poles around us to be

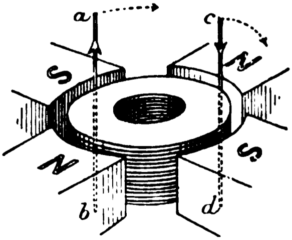


FIG. 211.—SKETCH OF 4-POLE FIELD.

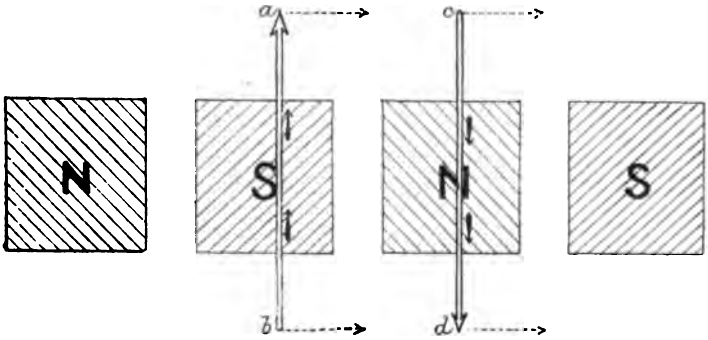


FIG. 212.—4-POLE FIELD DEVELOPED FLAT.

then laid out flat, as in Fig. 212. It will be noticed that the faces of the N and S poles are shaded obliquely for distinction.[1]

---

[1] I choose these oblique lines for the following reason. If instead of the line *a b* (representing a conductor), a narrow slit in a piece of paper were laid over the drawing of the pole-face, and moved as the dotted arrows show towards the right, the slit in passing over the oblique lines will cause an apparent motion in the direction in which the current tends in reality to flow. It is easy to remember which way the oblique lines must slope; for those on a N pole-face slope parallel to the oblique bar of the letter N.

Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wire. In the case of ring windings the wires which connect the active conductors in the gap-space pass through the central aperture in the ring when they are removed from the magnetic field. Suppose, for simplicity, we have a ring armature of only twelve turns, and 12 bars to the commutator. If this is opened out from the inside we shall have the form shown in Fig. 213, where the dotted lines are the inactive parts of the spiral winding that pass through the inside of the ring. By tracing the arrows it

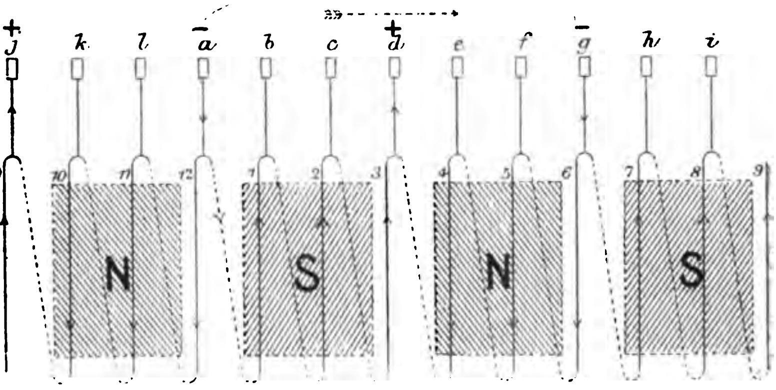


FIG. 213.—DEVELOPMENT OF RING-WINDING FOR 4-POLE MACHINE.

will be seen that there must be two positive and two negative brushes. Fig. 214 gives an end-view diagram of the same winding, by which the two modes of presentation may be compared. It is clear that in this case the armature might be used as two separate machines to furnish two separate currents, though this would not be desirable. It is usual to couple the positive brushes together, and the negative brushes together. A 6-pole machine would require six brushes, and so forth. The reader should examine what is said on this point on pages 404 to 406. When the brushes of the same sign are thus connected together the electromotive-force of the whole armature is simply that of any of the sets of coils from one

+ brush to the adjacent – brush. In this 4-pole machine the coils of the four quadrants are in four parallels; the internal resistance is one-sixteenth of the total resistance around the entire ring. There is, as we shall see, another mode of connecting the coils of a multipolar ring, in which the four sets of coils, instead of being all in parallel, are grouped in two series, so as to give two paths in parallel only. This mode is sometimes called *multipolar series*, or *two-circuit* winding; it would be more appropriately called *series-parallel grouping*. It requires only two sets of brushes at two neutral points on the commutator, however many poles there are around the ring.

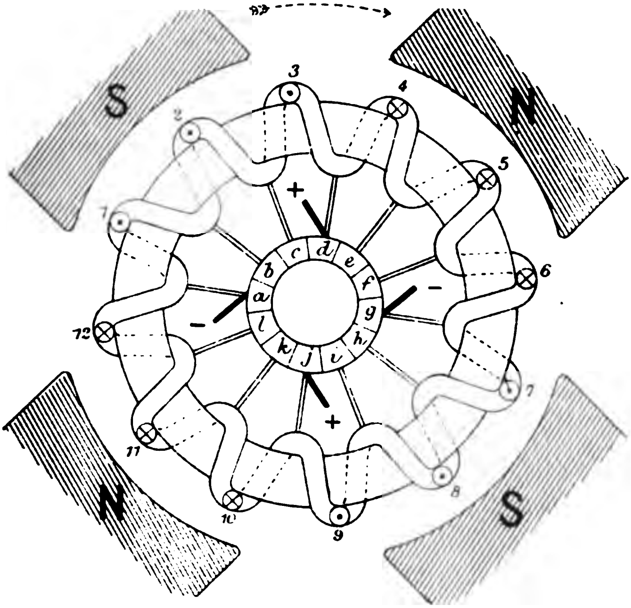


FIG. 214.—RING WINDING FOR 4-POLE MACHINE (CORRESPONDING TO FIG. 213).

In further applying the method of development to those cases in which the winding is entirely exterior to the core, as for drum armatures, or to those in which there is no core at all, namely for disk armatures, we find that there are two distinct modes of procedure, which we may respectively denote[1] as *lap-winding* and *wave-winding.* The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. If now we examine Fig. 215 we shall see that at the back of the armature (or end distant from the commutator) each conductor is united to one five places further on—No. 1 to No. 6, No. 3 to No. 8—and that at the front end the winding, after having made one "element" (as for example *d*–7–12–*e*), then forms a second element (*e*–9–14–*f*), which laps over the first; and so on all the way round until the winding returns on itself.

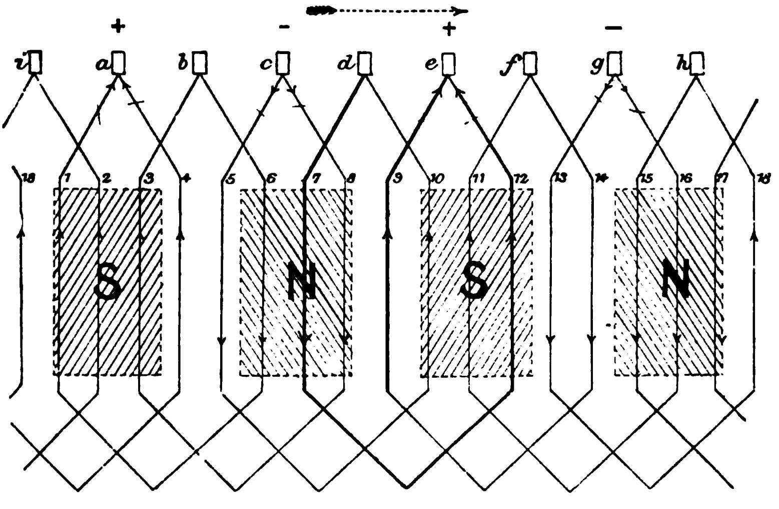


FIG. 215.—TYPICAL LAP-WINDING.

---

[1] The wave-winding is Fritsche's *Wellen-wickelung;* the lap-winding is called by Arnold (*op. cit.*) *Scheitel-wickelung.* Wave-windings were early used by Matthews, Bollmann and Müller; and by Ferranti and Lord Kelvin for alternate-current generators.

Now contrast with this Fig. 216, in which, though the connexions at the back end are the same, those at the commutator end are different. It will be seen that when the winding returns back toward the commutator, instead of lapping back toward the part from which it started, it is turned the other way. The winding *d*–7–12 does not return

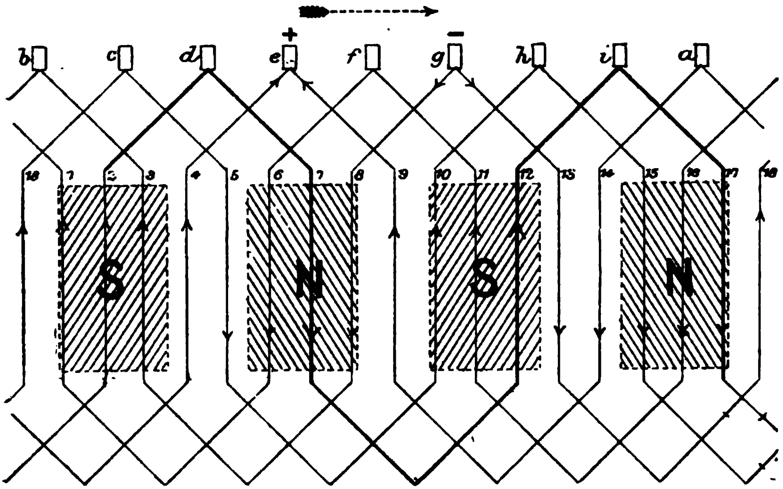


FIG. 216.—TYPICAL WAVE-WINDING.

WINDING-TABLE FOR FIG. 215.
(LAP-WINDING.)

F	B		F
+ *a*	1	6	*b*
b	3	8	*c*
− *c*	5	10	*d*
d	7	12	*e*
+ *e*	9	14	*f*
f	11	16	*g*
− *g*	13	18	*h*
h	15	2	*i*
i	17	4	*a*

WINDING-TABLE FOR FIG. 216.
(WAVE-WINDING.)

F	B		F
a	1	6	*f*
f	11	16	*b*
b	3	8	*g*
− *g*	13	18	*c*
c	5	10	*h*
h	15	2	*d*
d	7	12	*i*
i	17	4	*e*
+ *e*	9	14	*a*

at once to *e*, but goes on to *i*, whence another element *i*–17–4–*e* goes on in a sort of zig-zag wave. These are both drum windings, the corresponding tables being as shown on the preceding page.

It will be noted in passing that whilst with this particular number of conductors (18) the lap-winding results in four circuits in parallel, and needs four brushes, the wave-winding results in two circuits in parallel, and requires two brushes only.

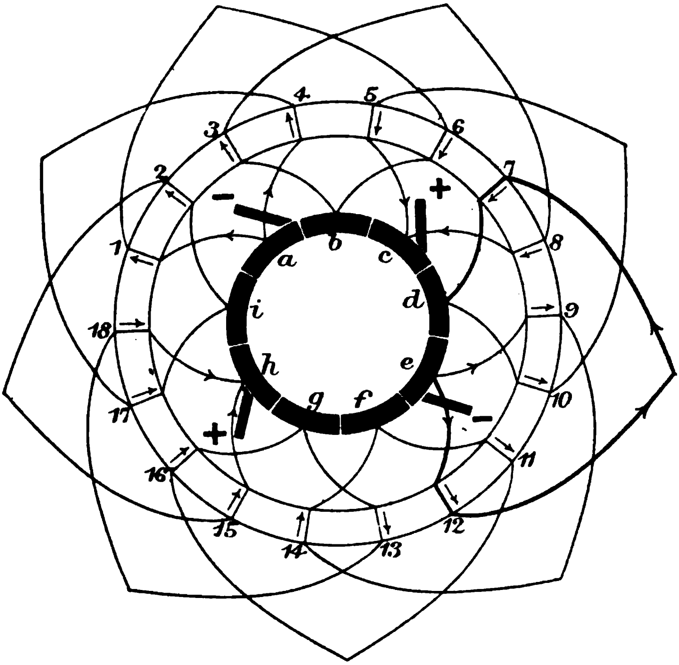


FIG. 217.—LAP-WINDING 4-POLE DRUM.

Radial Diagrams.—So far we have used, beside winding tables, two species of diagrams, one being merely a sort of end-view of the armature, the other the developed diagram. To these we must now add another, the radial diagram, in which the conductors of the armature are represented by short radial lines, while the end-connectors are represented by curves or zigzags, those at one end of the armature being drawn within, those at the other end being drawn without the periphery. With such diagrams it is easier to follow the circuits and to distinguish the back and front pitches of the winding. The arrows show the direction of the induced electromotive-forces. In Figs. 217 and 218 the armatures are supposed to be rotating in a 4-pole field.

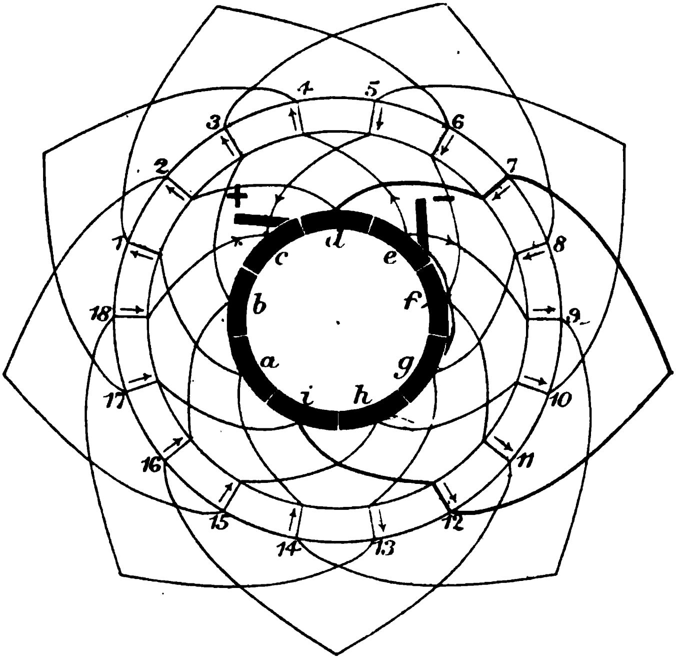


FIG. 218.—WAVE-WINDING 4-POLE DRUM.

Fig. 217 is a diagram of a lap-winding and Fig. 218 a wave-winding. It will be seen that while the lap-winding gives four circuits in parallel, the wave-winding gives but two circuits. It is a "series-winding" and gives with the same number of conductors double the electromotive-force; but, as the maximum permissible current of any one conductor is alike for the two machines, the series-winding, with only two circuits instead of four, will only yield half the total current of the parallel winding.

Field-Step.—It will be noted that whereas in ordinary ring-windings and in lap-windings the winding at the completion of each element comes back to a point close to that from which it started, and therefore in the *same polar region*, the wave-windings all step forward to the *next polar region* of the same name. There is no abstract reason why windings should not be imagined in which the step so made from one element of the winding to the next should not be to the region of a still more distant pole. Let m denote the number of such complete pole-pitches over which the step is made. Then, in general, we have for lap-windings $m = 0$; for wave-windings $m = 1$; and for ring-winding $m = 0$ for parallel grouping, or $m = 1$ for series grouping. The cases where $m > 1$ are not practical.

Groups of Conductors.—Suppose an armature to have Z conductors arranged in simple "elements" or "sections" consisting each of two conductors joined together as a loop, the commutator needed would have, therefore, K segments $= \frac{1}{2}$ Z. It is easy to see that, using the same commutator, one might double the number of conductors (and double the electromotive-force of the machine) by substituting for each "element" one consisting of four conductors wound as a double loop. Generalizing, we may say that if each "element" consists of a group of g conductors, if the number of such groups or elements be called G, then $Z = gG = gK$. In the case of ring-windings, where the simplest element is one turn, g may be any whole number, odd or even. For lap and wave-windings g must be an even number.

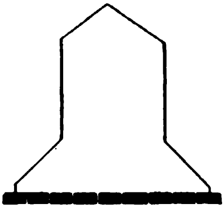


FIG. 219.

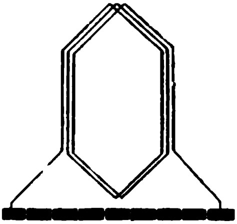


FIG. 220.

It is possible to go further, and imagine a mixed wave and lap-winding. For, beginning with a wave-winding, each element of which is a mere open loop of 2 conductors such as shown in Fig. 219, one can easily see that for it one might substitute a group of, say, six conductors consisting of three laps. Such groups are, indeed, frequently employed in practice, for generating high voltages, as for example in tram-car motors, and in the high-voltage generator of Brown (Fig. 479), since this arrangement lends itself readily to the winding of coils upon formers in the shop.

ARMATURE FORMULÆ.

Armature windings for continuous-current generators and motors may be classified under two heads :—

1. *Parallel Grouping.*
   - (*a*) Lap-windings (drum or barrel-winding).
   - (*b*) Ring-windings.
2. *Series-Parallel Grouping.*
   - (*a*) Wave-windings (drum or barrel-winding).
   - (*b*) Series ring-windings.

A mixed lap and wave-winding is sometimes used for grouping former-wound coils.

For a machine of prescribed speed and voltage the number of armature conductors necessary to produce the given voltage will depend not only on the number of poles and on the magnetic flux per pole, but on the grouping adopted for the conductors. The formulæ connecting these quantities are as follows, the symbols used having the following meanings :

E = the prescribed number of volts to be generated.
n = number of revolutions *per second.*
p = the number of poles.
c = the number of *circuits* or paths that are in parallel through the armature from brush to brush.
C_a = the whole current carried by the armature.
Z = the whole number of conductors carried in the slots of the armature.

K = the number of segments in the commutator.

N = the magnetic flux per pole, meaning the total number of magnetic lines that reach the armature from one pole.

The current in any one conductor will obviously be equal to $C_a \div c$.

The general formula then is

$$E = n \times Z \times N \times \frac{p}{c} \div 10^8 \quad . \quad . \quad . \quad (1)$$

whence

$$Z = \frac{c \times E}{n \times p \times N} \times 10^8 \quad . \quad . \quad . \quad . \quad (2)$$

In ordinary parallel groupings (lap-wound drum-armatures, and ring-armatures) $c = p$, so that for these the formula (2) is simplified down to

$$Z = \frac{E \times 10^8}{n N} \quad . \quad . \quad . \quad . \quad (2a)$$

Examples.—(1) In a parallel-wound armature of a 12-pole tramway generator of the English Electric Manufacturing Co. (M P 12—1100—100); $E = 550$; $n = 1 \cdot 666$; $N = 25,647,000$; $p = 12$; $c = 12$; hence by formula (2) or (2*a*) $Z = 1248$.

(2) In the series-parallel armature of the 10-pole tramway generator of Kolben and Co., p. 671 (M P 10—250—125); $E = 550$; $n = 2 \cdot 083$; $N = 12,110,000$; $p = 10$; $c = 4$; hence by formula (2) $Z = 874$.

(3) In the series-parallel armature of the 12-pole tramway generator of the Oerlikon Co., p. 654 (M P 12—500—100); $E = 550$; $n = 1 \cdot 666$; $Z = 1326$; $p = 12$; $c = 6$; hence by formula (1) $N = 12,445,000$.

WINDING FORMULÆ.

Terms used in the Theory.—It is essential to understand the terms and the sense in which they are used.

Any winding is said to be *re-entrant* which returns on itself so as to form a closed coil. An armature-winding is said to be *singly re-entrant* if it re-enters itself after simply passing in regular order through all the coils arranged around the armature core. Thus an ordinary Gramme ring, or a simple lap-wound drum-armature (Fig. 217), is singly re-entrant. There may, if used in a multipolar field, with several sets of brushes at the commutator, be various paths through it; but so far as re-entrancy is concerned it is singly re-entrant. The symbol for a singly re-entrant winding is O.

An armature may be wound with two independent circuits each of which is singly re-entrant. Fig. 221 shows a ring-armature wound thus. These two windings *might* have been furnished with two independent commutators, one at each end. But instead, the number of commutator segments is doubled, the two sets of bars being alternated or imbricated between one another. The brushes must be made broad enough to overlap at least 2½ bars of the commutator, so as to collect from both windings simultaneously. In a two-pole field, with two sets of broad brushes, this armature would give four paths in parallel from brush to brush. Such a winding is described as *duplex*, with symbol O O. The odd numbers form one winding, the even numbers another. Three independent windings with three sets of commutator bars similarly imbricated would be called a *triplex* winding, for which the symbol is O O O.

An armature is said to be *doubly re-entrant* if its winding only re-enters on itself after having made two passages around the coils of the armature. This term is best elucidated by the example of Fig. 222. This consists of a ring-winding in 17 groups. They are joined together in a way precisely akin to the duplex winding just described; each coil being joined to the next but one, but not to the one immediately next to it. But as the total number of sections is uneven, the coils do not form two separate windings. If we begin with the coil numbered 1, we see it is joined to 3, 5, 7, 9, etc. until we come to number 17, by which time it has completed one round of the periphery, but is not yet re-entrant, for now it goes on to the coils 2, 4, 6, etc., to coil 16, from which it finally re-enters the starting point. The symbol for such a *doubly re-entrant* winding is ◎ . This winding will also require broad brushes that bridge over more than two sections of the commutator at one time. Like the duplex winding of Fig. 221, it doubles the number of paths from brush to brush. In fact, it is electrically the equivalent of a duplex winding save for the fact that it requires an odd number of coils. In

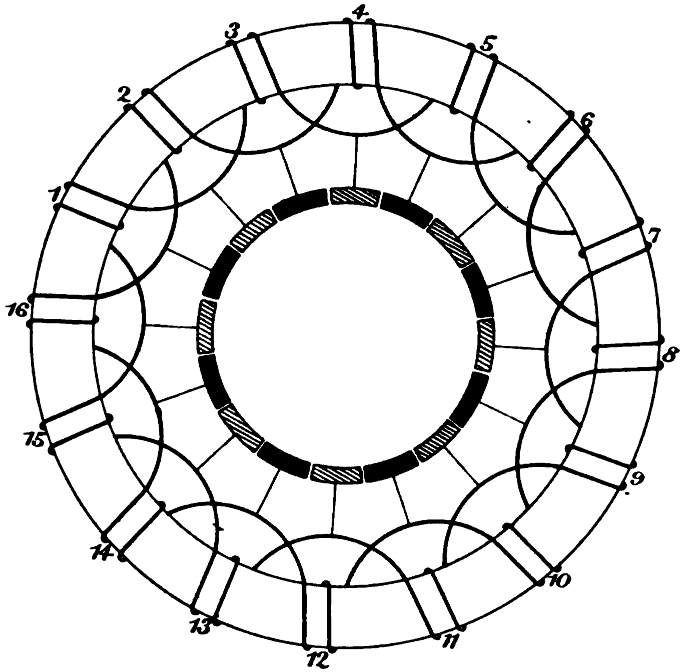


FIG. 221.—DUPLEX WINDING, CONSISTING OF TWO SINGLY RE-ENTRANT RING WINDINGS.

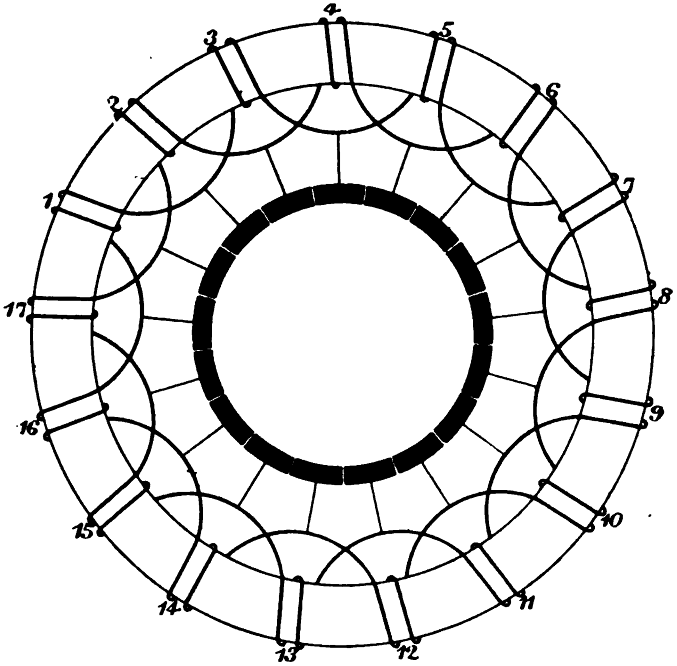
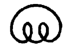


FIG. 222.—DOUBLY RE-ENTRANT RING WINDING.

armatures of many turns this difference is quite immaterial. For example, an armature with 200 coils as a duplex singly re-entrant winding, and a simplex doubly re-entrant armature with 201 coils, if revolved at the same speed in the same field would only differ by ½ of 1 per cent. in their electromotive-force. Lap-windings may also be made doubly re-entrant, see Fig. 225, p. 379. A *trebly re-entrant* winding might be made by choosing the number of sections so as to become re-entrant only after a travel completing three rounds of the periphery. For example, a 20-coil ring-winding joined according to the following scheme: 1—4—7—10—13—16—19—2—5—8—11—14—17—20—3—6—9—12—15—18—1. The symbol for treble re-entrancy is  . It is the electrical equivalent of a triplex-winding made of three simplex singly re-entrant windings O O O; and like the triplex-winding will require brushes broad enough to cover 3½ adjacent commutator bars *at least.*

Armature windings are also described in terms of the *number of paths* which they afford for the current to follow from the negative brushes through the windings to the positive brushes. This number, in closed coil armatures (which are the only ones here dealt with) is always even. In simplex parallel-wound armatures (whether ring or drum) the number of such paths or circuits is always equal to the number of poles: in duplex parallel-wound armatures to twice the number, and so forth. In simplex series-wound armatures the number of such paths is always two: in duplex series-wound armatures, four, irrespective of the number of poles. It is common to refer to windings by the number of circuits they present: thus, one speaks of a *ten-circuit* winding, meaning one in which there are ten paths through the winding from − to +. The current in one circuit will be equal to the whole armature current divided by the number of circuits. There are also methods of winding due to Arnold, which result in a *series-parallel arrangement.* Thus it is possible to have a 6-pole machine, with 4 paths through the armature. This might be carried out as a doubly re-entrant wave-winding. (See p. 380.)

The next term which requires definition is the *pitch* or *spacing* of the winding. This term denotes the distance from one element of the winding to the next similar element in the succession; and it is usual to express the *pitch* of the winding in terms of the number of conductors spanned over, or less usually in terms of the number of elements of winding (loops, or groups of conductors) passed over, or sometimes in terms of the number of slots passed over. It is not usual to express the pitch, either in actual peripheral length, or in terms of angle subtended, or in terms of the pole-pitch. Suppose all the conductors to be numbered consecutively around the periphery of an armature, and that No. 1 is joined at the front end to No. 16, thus forming a loop, and that No. 16 is joined at the back end to No. 31, then the pitch at both ends is 15. In wave-winding the pitch at both ends is positive, that is to say the winding goes continually forward. In lap-winding the pitch at the two ends is different. Thus, if at the front end No. 1 is joined to No. 18, and if at the back of No. 18 the end connexion laps back to No. 3, the front pitch is + 17, while the back pitch is − 15. In that case the resultant pitch is 2, and the average pitch is 16. We shall use the symbols y_1 and y_2 for the front and back pitches respectively, y for the total pitch and $\bar{y}$ for the average pitch. Since it is obvious that the simplest element, whether of lap or wave-winding, is a loop of two conductors united together, and since in every such loop one of the two conductors ought to be passing a south pole at the time when the other is passing a north pole, it follows that the width across the loop ought to be approximately equal to the pole-pitch. In fact the average winding-pitch must be in lap-windings a little less, and in wave-windings a little less or a little greater, than the pole-pitch. In lap-windings the larger of the two pitches may equal the pole-pitch, ought not to exceed it, but may be less, in which case it is known as *fractional pitch*; while the smaller of the two pitches should not be less than the width of the pole-face.

Condition of Re-entrancy.—The condition that a winding shall return after a finite number of symmetrically spaced steps to the conductor from which it starts may be stated thus:—The resultant step from element to element, multiplied by the number of conductors per element, and by the number of such resultant steps, must equal the whole number of conductors multiplied by some whole number. For example, let a lap-winding consist of 80 simple loops, having a resultant pitch = 2. This will be re-entrant if the whole number of such conductors is 160. In the case of *wave-windings*, where the loops go zig-zagging around the periphery, the number of elements per round, multiplied by the number of rounds, and by the number of conductors per element, will obviously give the whole number of conductors so united. Now the pitch must be such as to be approximately equal to the pole-pitch but not exactly, otherwise the winding would become re-entrant at the first round. Or conversely, the whole number of conductors must be such that with a winding-pitch approximately equal to the pole-pitch, the winding shall become re-entrant only after a number of rounds. Thus, for example, in an 8-pole machine, with single winding pitch 25, the total number of conductors must *not* be 25 × 8 = 200, otherwise the winding would re-enter after the first round of 4 loops. It might be either 198 or 202, for then round after round would be completed before re-entrancy was finally attained. This example illustrates so well the essential principle of a simplex wave-winding that it may be further considered. Suppose we construct a winding table for this winding, using 202 = Z. Take the even numbers of the conductors as going down from front to back; the ~~even~~ numbers being the return conductors leading up from back to front. Starting with No. 1 the connexions run as follows: 1—26—51—76—101—126—151—176—201, the eighth step thus completing the first round, and failing to re-enter by 2 places. The second round of eight steps similarly goes from 201 to 199, the third to 197, and so forth. The winding thus recedes 2 places at each round. By the end of the twenty-fifth round 200 steps will have been taken, and the winding will have slipped back 50 conductors from No. 1, and the 200th step will therefore end on No. 153. There remain two steps to be taken, viz. from 153 to 178, and from 178 to No. 1, thus finally completing the re-entrancy. Fig. 223 illustrates the

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS; TWO-CIRCUIT, SERIES-PARALLEL GROUPING; BRUSHES (±) 135° APART.

F B F B F B F B F

D	U	D	U	D	U	D	U
1	26	51	76	101	126	151	176
201	24	49	74	99	124	149	174
199	22	47	72	97	122	147	172
197	20	45	70	95	120	145	170
195	18	43	68	93	118	143	168
193	16	41	66	91	116	141	166
191	14	39	64	89	114	139	164
189	12	37	62	87	112	137	162
187	10	35	60	85	110	135	160
185	8	33	58	83	108	133	158
183	6	31	56	81	106	131	156
181	4	29	54	79	104	129	154
179	2	27	52	77	102	127	152
177	202	25	50	75	100	125	150
175	200	23	48	73	98	123	148
173	198	21	46	71	96	121	146
171	196	19	44	69	94	119	144
169	194	17	42	67	92	117	142
167	192	15	40	65	90	115	140
165	190	13	38	63	88	113	138
163	188	11	36	61	86	111	136
161	186	9	34	59	84	109	134
159	184	7	32	57	82	107	132
157	182	5	30	55	80	105	130
155	180	3	28	53	78	103	128
153	178	1					

first two rounds of this winding. It is assumed, but not shown, that the winding is in two layers; the conductors in the upper layer being those with odd numbers, those in the under layer with the even numbering. On examining this table it will be seen that the conductor which is half-way through the winding from No. 1, is No. 102. These are not at opposite ends of a diameter, but are ⅝ of a circumference apart. As a matter of fact the brushes—two sets of which only are essential, as there are only two circuits through the winding—may be either ⅛, ⅜ or ⅝ of a circumference apart. In one sense this winding has a 25-fold re-entrancy, seeing that at every 8 steps

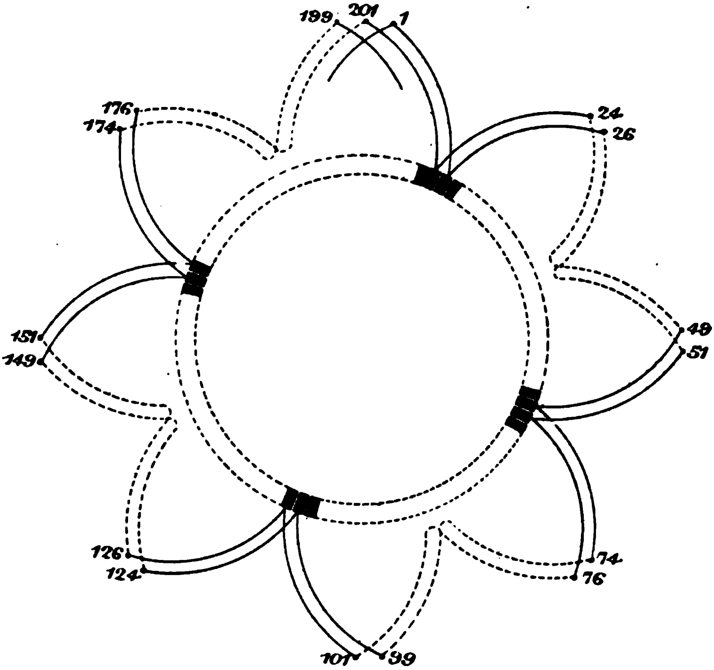


FIG. 223.—WAVE-WINDING: 8-POLE, 2-CIRCUIT, SINGLY RE-ENTRANT.

the periphery is perambulated. But, strictly, the winding is only singly re-entrant. Had there been 204 conductors, or 196 conductors, so that at each round of eight steps the winding receded or advanced by four places (instead of two places), the result would have been different, giving a winding with four paths instead of two. The number of paths through the armature corresponds to the number 2, 4, or 6, etc., by which the first round fails of re-entrancy. In the case illustrated by the winding table we see that the principle of re-entrancy enunciated at the beginning of this paragraph is fulfilled, for the resultant step of 30 multiplied by the number (which is 2) of conductors per element, multiplied by the number of resultant steps, namely (25 × 4) + 1, makes 6060, which is an integral multiple of the whole number of conductors, 202.

Condition of each Conductor being encountered once.—It is not enough that the winding should be re-entrant. It should (in a simply re-entrant winding) be such that *all* the conductors should be encountered, and that each should be encountered once only.

Case I. Lap-Windings.—Let y_1 be the forward pitch and y_2 the backward pitch, its actual value being negative. Then $y_1 + y_2$ is the resultant step. If we confine ourselves to the practical case that each element or section of the winding is a simple loop, the number s of such sections will be equal to $\frac{Z}{2}$; and the number of sections (which is the same as the number of resultant steps if multiplied by the length of each resultant step) will equal the total travel of the winding. This will be equal to Z if the winding is singly re-entrant. But if the lap has been such (for example if y_1 is 25 and y_2 is -21, then $y_1 + y_2 = 4$) that re-entrancy is not effected without travelling more than once round the periphery, then the total travel will be equal to U Z, where U is the number of times the periphery has been travelled round. This gives us as the first condition that

$$\frac{Z}{2}(y_1 + y_2) = U\,Z;$$

whence

$$\frac{y_1 + y_2}{2} = U. \qquad \qquad (1)$$

Now U may be 1, 2, or any whole number; hence it follows that $y_1 + y_2$ must in *every* case be an *even* number. Further, the condition that no conductor shall be encountered twice is that for no number of steps whatever shall $y_1 + y_2$, however often repeated, be equal to y_1. Or taking m as any whole number

$$m\,(y_1 + y_2) \gtrless y_1\,;$$

whence

$$\frac{y_1}{y_2} \gtrless \frac{m}{1-m}. \qquad . \quad . \quad . \quad (2)$$

It follows from this inequality that y_1 and y_2 *cannot possibly have any common factor*, and as their difference must be even, it follows that *both of them must be odd numbers*; and to make the winding lap back one of them must be a negative number. For example, if $y_1 = 29$ and $y_2 = -27$, then $y_1 + y_2 = 2$.

Case II. Wave-Windings.—The resultant step for an element being $y_1 + y_2$, and the number of such steps being $\frac{Z}{2}$ and the total travel being U times round the periphery, we have

$$\frac{Z}{2}\,(y_1 + y_2) = \mathrm{U\,Z}\,;$$

whence also

$$\frac{y_1 + y_2}{2} = \mathrm{U}. \qquad . \quad . \quad (3)$$

In the case of the winding table given above where y_1 and y_2 are each 25, the total travel is 25 times round the periphery. Now, in order that no conductor be encountered twice it is clear that not by any number of repetitions of the step $y_1 + y_2$ shall it be possible to recur to the step y_1 beyond any previous number of the repetitions of the step $y_1 + y_2$. Or, if m and n are any whole numbers it is clear that m times $y_1 + y_2$ must *not* equal n times $y_1 + y_2$ steps plus y_1. Or in symbols

$$m\,(y_1 + y_2) \gtrless n\,(y_1 + y_2) + y_1 \quad . \quad . \quad (4)$$

It follows that in this case also y_1 and y_2 *cannot have any common factor*; and as U may be any number, odd or even, it follows from (3) that as their sum must be even, both of them may be odd. They may be, however, equal to one another and this is the common case.

General Formulæ.—We are now ready to state the general formulæ for windings. These may be put either (1) in terms of the number of segments K of the commutator, and of the pitch of the winding y_k in terms of the number of commutator segments over which the element of the winding spans, or (2) in terms of the number of conductors Z and of the pitches y_1 and y_2 as defined above.

These general formulæ are as follows:—

If y stands for the complete step, not from conductor to conductor, but from the first conductor of any group to the first conductor of the next group, m for the field step, and G for the total number of groups in the winding, we shall have

$$\tfrac{1}{2}py \pm c = mgG = mZ \quad . \quad . \quad (1)$$

when

$$Z = \frac{py \pm 2c}{2m}; \quad . \quad . \quad . \quad (2)$$

and

$$y = \frac{2mZ \mp 2c}{p} \quad . \quad . \quad . \quad (3)$$

which are the general formulæ for symmetrical windings.

For *lap-windings* $m = 0$, whence it follows that

$$y = \mp\frac{2c}{p}; \quad . \quad . \quad . \quad . \quad (4)$$

y being dissected into 2 parts y_1 and y_2, of which y_2 is negative, each of which is either equal to or slightly less than Z/p, and which differ from one another by $2c \div p$.

In lap-windings the step of the winding at the commutator is related to winding pitch by the simple rule:—

$$y_k = y \div g. \quad . \quad . \quad . \quad (5)$$

Thus in a simple lap-winding, where $y = 2$, and where each element of the winding is a simple loop made of two conductors so that $g = 2$, we have $y_k = 1$.

For *wave-windings* $m = 1$, so that the complete step becomes

$$y = \frac{2Z \mp 2c}{p}; \quad . \quad . \quad . \quad (6)$$

and if this is made up of two equal back and front pitches y and y_2 of equal value, we shall have

$$y_1 = y_2 = \frac{Z \mp c}{p}. \quad . \quad . \quad . \qquad (7)$$

LAP-WINDINGS.

(*i.*) *Simplex Singly Re-entrant* (Parallel) *Lap-Winding.*

$c = p$; $m = 0$; and, if $g = 2$; $Z = 2G = 2K$.

$$y = \pm 2;$$

$$y_1 \overset{=}{<} \frac{Z}{p} \qquad \text{and must be } \textit{odd};$$

$$-y_2 = y_1 \pm 2$$

$$y_k = 1.$$

(*ii.*) *Duplex or Multiplex* (Parallel) *Lap-Winding,* consisting of x independent windings, each of which is a simplex singly re-entrant lap-winding.

$c = px$; $m = 0$; and if $g = 2, Z = 2G = 2K$.

$$y = \pm 2x;$$

$$y_1 \overset{=}{<} \frac{Z}{p} \qquad \text{and must be } \textit{odd};$$

$$y_2 = y_1 - 2x;$$

$$y_k = \pm x.$$

(*iii.*) *Simplex* (Series-Parallel) *Doubly or Multiply Re-entrant Lap-Winding.* (See remark on p. 367 as to meaning of term). $c = 4, 6$, or other even number greater than 2; $m = 0$; and, if

$$g = 2, Z = 2G = 2K.$$

$$y = \pm c;$$

$$y_1 \overset{=}{<} \frac{Z}{p} \qquad \text{and must be } \textit{odd};$$

$$y_2 = y_1 - c;$$

$$y_k = \pm \tfrac{1}{2}c.$$

(*iv.*) *Duplex or Multiplex* (Series-Parallel) *Doubly or Multiply Re-entrant Lap-Winding*, consisting of x independent windings, each of which is a simplex doubly or multiply re-entrant lap-winding. Here $x = 2, 3, 4$ or any whole number; $c_1 =$ the number of circuits through any one of the independent series-parallel windings (may be 4, 6, or other even number higher than 2); $m = 0$; and if $g = 2$, $Z = 2G = 2K$.

$$y = \pm x c_1;$$

$$y_1 \gtreqless \frac{Z}{p} \qquad \text{and must be } odd;$$

$$y_2 = y_1 - x c_1;$$

$$y_k = \pm \tfrac{1}{2} x c_1.$$

Figs. 224 and 225 afford examples of case (*ii.*) and case (*iii.*) above. Fig. 224 is a duplex lap-winding in which $p = 4$, $Z = 32$, $y_1 = +9$ and $y_2 = -5$. There are two independent circuits exactly as in the duplex ring-winding, Fig. 221, p. 368. Symbol O O. Fig. 225 corresponds to the doubly re-entrant ring-winding, Fig. 222, p. 368. In it $p = 4$, $Z = 34$, $y_1 = +9$ and $y_2 = -5$. Symbol ◎ . In both cases $c = 8$.

WAVE-WINDINGS.

(*i.*) *Simplex Singly Re-entrant* (Series) *Wave-Winding.*

$c = 2$; $m = 1$; and if $g = 2$, $Z = 2G = 2K$.

$\bar{y}$ is the average of y_1 and y_2.

$$Z = p\bar{y} \pm 2;$$

$$y_1 = y_2 = \frac{Z \mp 2}{p} \qquad \text{and must be } odd\text{, and must not have any common factor with } Z.$$

$$y_k = \frac{2K \mp 2}{p}.$$

(*ii.*) *Duplex or Multiplex* (Series) *Wave-Winding*, consisting of x independent singly re-entrant simplex wave-windings.

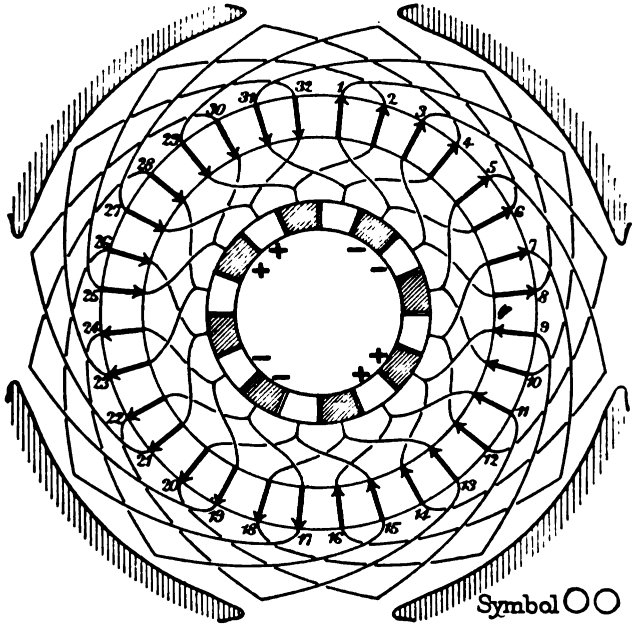


FIG. 224.—DUPLEX LAP-WINDING.

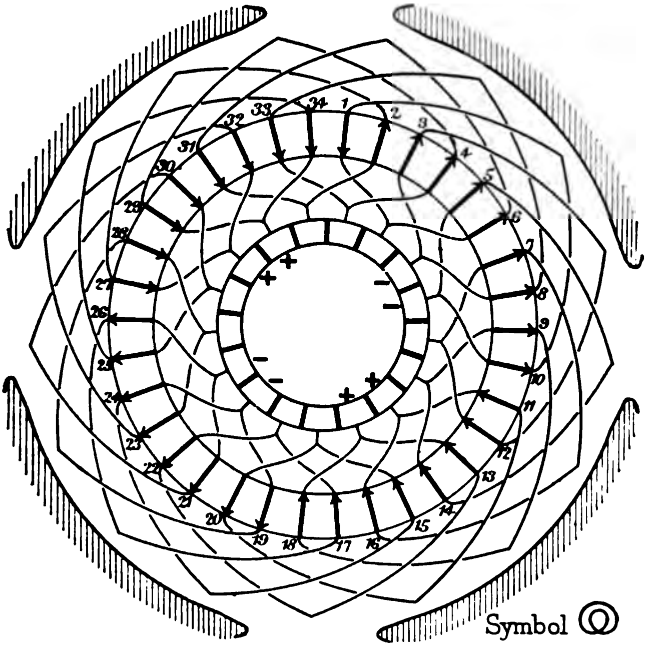


FIG. 225.—SIMPLEX DOUBLY RE-ENTRANT LAP-WINDING.

$x = 2, 3, 4,$ or any whole number; the number of circuits c_1, in any one of the simplex windings $= 2$; $m = 1$; and if $g = 2$ then $Z = 2G = 2K$. Number of circuits in parallel $= c_1 x$.

$$Z = xp\bar{y} \pm 2x;$$

$$y_1 = y_2 = \frac{Z \mp 2x}{xp};$$ in those cases where $\bar{y}$ is even, y_1 may $= \bar{y} + 1$ and $y_2 = \bar{y} - 1$.

$$y_k = \frac{2K \mp 2x}{xp}.$$

(*iii.*) *Simplex Doubly or Multiply Re-entrant* (series-parallel) *Wave-Winding*; also called *Arnold's Winding.*

$c = 4, 6,$ or other even number higher than 2; $m = 1$; and, if $g = 2$, $Z = 2G = 2K$.

$$Z = p\bar{y} \pm c;$$

$$y_1 = y_2 = \frac{Z \mp c}{p};$$

$$y_k = \frac{2K \mp c}{p}.$$

(*iv.*) *Duplex or Multiplex Doubly or Multiply Re-entrant* (Series-Parallel) *Wave-Winding*, consisting of x independent wave-windings each of which is doubly or multiply re-entrant.

$c_1 = 2, 4, 6,$ or other even number; number of circuits in parallel $= c_1 x$; $m = 1$; if $g = 2$, then $Z = 2G = 2K$.

$$Z = xp\bar{y} \pm c_1 x;$$

$$y_1 = y_2 = \frac{Z \mp c_1 x}{xp};$$

$$y_k = \frac{2K \mp c_1 x}{xp}.$$

RING-WINDINGS.

(*i.*) *Parallel Grouping* (Simplex).

$c = p$; $m = 0$; and if each element is of one turn only $g = 1$, whence $Z = G = K$; the only possible values of the pitch are—

$$y = \pm 1;$$

$$y_k = \pm 1.$$

(*ii.*) *Series Grouping* (Singly Re-entrant).

$c = 2$; $m = 1$; and if $g = 1$, $Z = G = K$.

$$Z = \frac{py \pm 2}{2};$$

$$y = \frac{2Z \mp 2}{p}, \quad \text{and must be } \textit{odd}.$$

If, as in some high-voltage machines, each of the windings consists of g turns, then $Z = gG = gK$, and

$$y_k = \frac{2K \mp 2}{p}.$$

(*iii.*) *Series-Parallel Grouping* (Doubly or Multiply Re-entrant Simplex Ring-Winding.)

$c = 4, 6, 8$ or other even number higher than 2; $m = 1$.

$$Z = \frac{py \pm c}{2};$$

$$y = \frac{2Z \mp c}{p};$$

$$y_k = \frac{2K \mp c}{p}.$$

(*iv.*) *Duplex or Multiplex Parallel Grouping.*

If there are to be n independent circuits in the winding, then the number of circuits in parallel will be $np = c$.

Assuming $g = 1$, we have

$$\left.\begin{array}{l} y = \pm n \\ y_k = \pm n \end{array}\right\}; \quad \text{or if } g \text{ is not} = 1, \quad y = \pm g n;$$

(*v.*) *Duplex or Multiplex Series Grouping*, consisting of n independent windings, each of which is a simplex singly re-entrant series winding. The number of circuits in parallel will be $= 2\,n$; $m = 1$; and if $g = 1$,

$$Z = \frac{npy \pm 2\,n}{2};$$

$$y = \frac{2\,Z \mp 2\,n}{np};$$

$$y_k = \frac{2\,K \mp 2\,n}{p}.$$

(*vi.*) *Duplex or Multiplex Series-Parallel Grouping.*—Here $n =$ the number of independent windings (2, 3, 4, or any whole number); $c_1 =$ the number of circuits through any one of the independent windings (may be 4, 6, 8, or any even number higher than 2); the number of circuits in parallel through the armature will be $= c_1\,n$; $m = 1$; and if $g = 1$, then :

$$Z = \frac{npy \pm 2\,c_1\,n}{2};$$

$$y = \frac{2\,Z \mp 2\,c_1\,n}{np};$$

$$y_k = \frac{2\,K \mp 2\,c_1\,n}{np}.$$

The circumstance that if in a wave-winding $\bar{y}$ and Z have any common factor there will be a corresponding number of independent windings, leads to some curious results. Further, the circumstance that if in any wave-winding the number of circuits is made equal to the number of poles, leads to the result that in this case the wave-winding becomes identical to a simple lap-winding or ring-winding. In the case of bipolar machines wave- and lap-windings are identical, the only difference being the question whether $y_1 = y_2$ or not. A series grouping cannot be effected by a lap-winding: it may be effected by a wave-winding or by a mixture of wave and lap-winding. In the case of 4-pole, 8-pole and 12-pole machines, a simplex series winding cannot be made with 4 conductors per segment of the commutator. Nor, in the case of 6-pole and 12-pole machines, can a simplex series winding be made with 6 conductors per segment. In general, for a machine with p poles or $2\,p$ or $3\,p$ poles, it is impossible to make a two-circuit winding having p conductors per segment of the commutator. Or, stated another way, to make a two-circuit wave-winding, the number of conductors must not be a multiple of the number of poles.

The number of circuits made by any winding can be calculated by the following formulæ, derived from those previously given.

Lap-Windings.

$$c = \tfrac{1}{2} p y. \quad . \quad . \quad . \qquad (\alpha)$$

Wave-Windings.

$$c = Z - p y_1 \quad . \quad . \qquad (\beta)$$

if $y_1 = y_2$. If not, then take instead of y_1 the *average* pitch.

Ring-Windings (*parallel*).

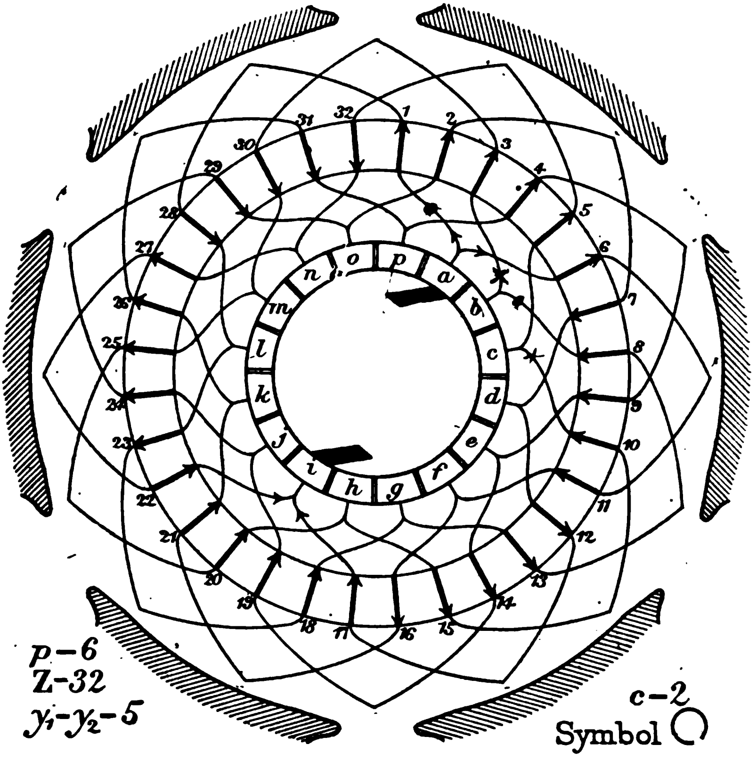
$$c = p y. \quad . \quad . \quad . \qquad (\gamma)$$

Examples:—(*i.*) $p = 6$; $Z = 374$; $K = 187$; $y_1 = 47$, $y_2 = -45$; $c = 6$. Here $y = 2$, the winding being a simple lap-winding.

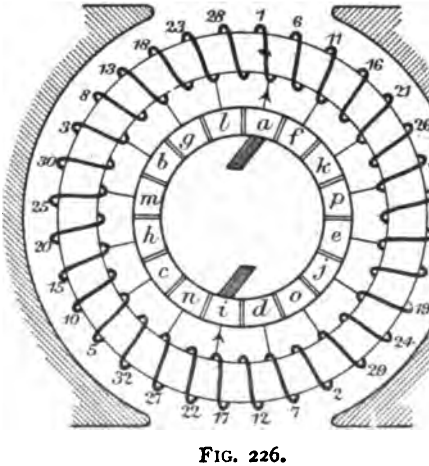
(*ii.*) $p = 6$; $Z = 434$; $y_1 = 73$, $y_2 = 71$. This is a wave-winding with average pitch of 72. Hence by formula (β), there will be two circuits only, the winding being singly re-entrant. Symbol O.

(*iii.*) $p = 6$; $Z = 442$; $y_1 = 71$; $y_2 = -67$. This is a lap-winding, with $y = y_1 + y_2 = 71 - 67 = 4$. Hence by formula ($\alpha$) there will be 12 circuits, the winding being duplex singly re-entrant. Symbol O O.

(*iv.*) $p = 8$; $Z = 572$; $y_1 = 71$, $y_2 = 71$. This is a wave-winding, giving by formula (β) 4 circuits, the winding being doubly re-entrant. Symbol ◎ .

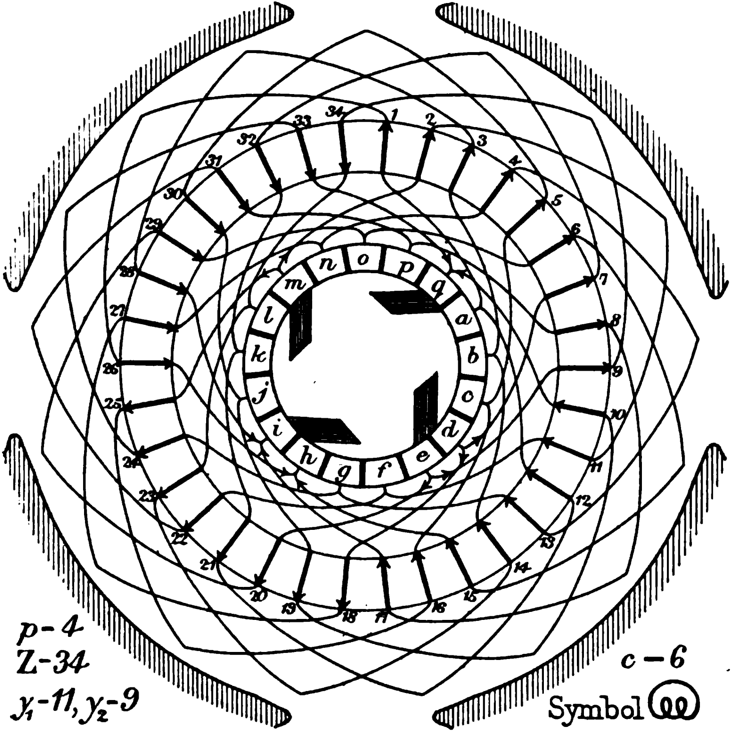


TWO-CIRCUIT. SIMPLEX, SINGLY RE-ENTRANT.



The Equivalent Ring Winding

FIG. 226.



SIX-CIRCUIT. SIMPLEX, TREBLY RE-ENTRANT.

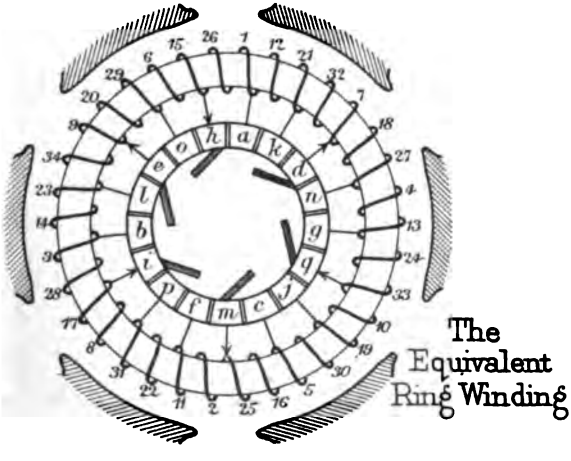
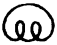


FIG. 227.

(*v.*) $p = 4$; $Z = 246$; $y_1 = 61$, $y_2 = 59$. This is a wave-winding with average pitch 60, giving 6 circuits, with a trebly re-entrant winding. Symbol  .

(*vi.*) $p = 4$; $Z = 438$; $y_1 = y_2 = 111$. This is a wave-winding, but as Z and y_1 contain 3 as a common factor there will be 3 independent wave windings, each singly re-entrant; and there will be 6 circuits. Symbol O O O.

Coloured Figures.—Figs. 226 to 231 give a set of examples of wave-windings to elucidate the rules.

Fig. 226 is a 6-pole, two-circuit winding (sometimes called "multipolar series"), with 32 conductors. The winding is singly re-entrant. The winding pitch $y_1 = y_2 = 5$. Hence by the rule $c = Z - py$, there will be two circuits. Below the figure is shown the equivalent ring, having the 32 conductors rearranged in the order of their occurrence (see Arnold's "reduced scheme," p. 415), the two circuits implying a two-pole field. The advantage of this mode of representation is that in the equivalent ring the windings do not overlap one another.

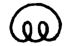
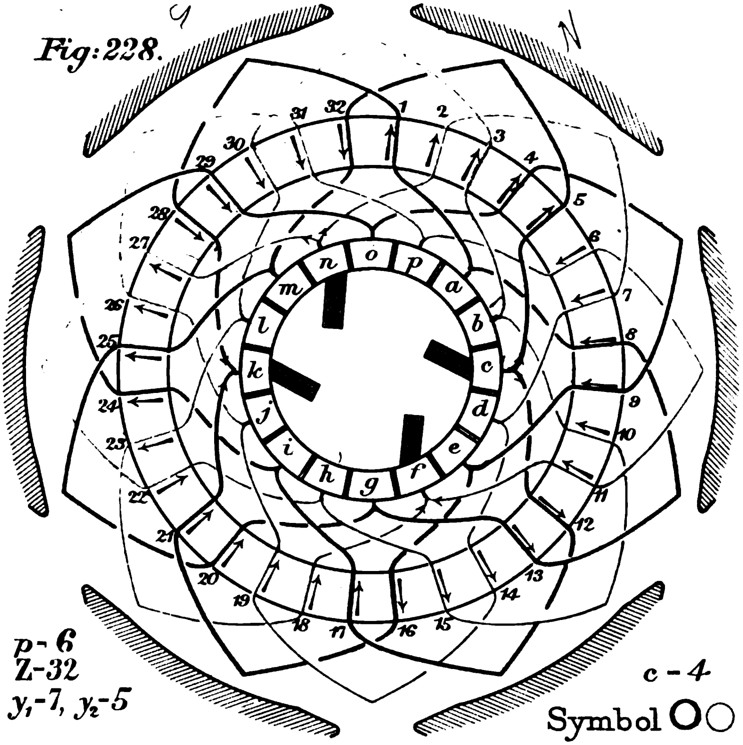
Fig. 227 depicts a 4-pole, six-circuit winding, with 34 conductors and an average winding-pitch of 10. On examination it will be seen that the winding, though simplex, is trebly re-entrant (symbol ), making 6 circuits though there are only 4 brushes, in correspondence with the 4 poles. The equivalent ring, as shown, will be a 6-pole ring with 6 brushes.

Fig. 228 is a 6-pole, four-circuit winding, having 32 conductors with an average winding pitch of 6. This produces a duplex-winding; there being two independent windings each singly re-entrant. Hence there are four circuits (symbol O O). The equivalent ring will, of course, have a 4-pole field and 4 brushes.

Fig. 229 is a 4-pole, eight-circuit winding, having 32 conductors, with an average winding pitch of 10. It results in a duplex, doubly re-entrant winding (symbol). The equivalent ring has 8 poles and 8 brushes.

Fig. 230 is a 4-pole, six-circuit winding, with 30 conductors and a winding-pitch of 9. As there is the common factor 3

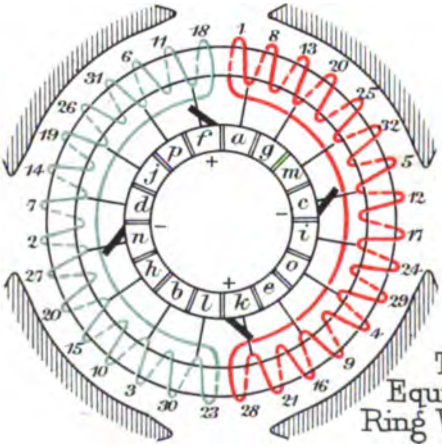
Fig: 228.



p - 6
Z - 32
y_1 - 7, y_2 - 5

c - 4
Symbol ○○

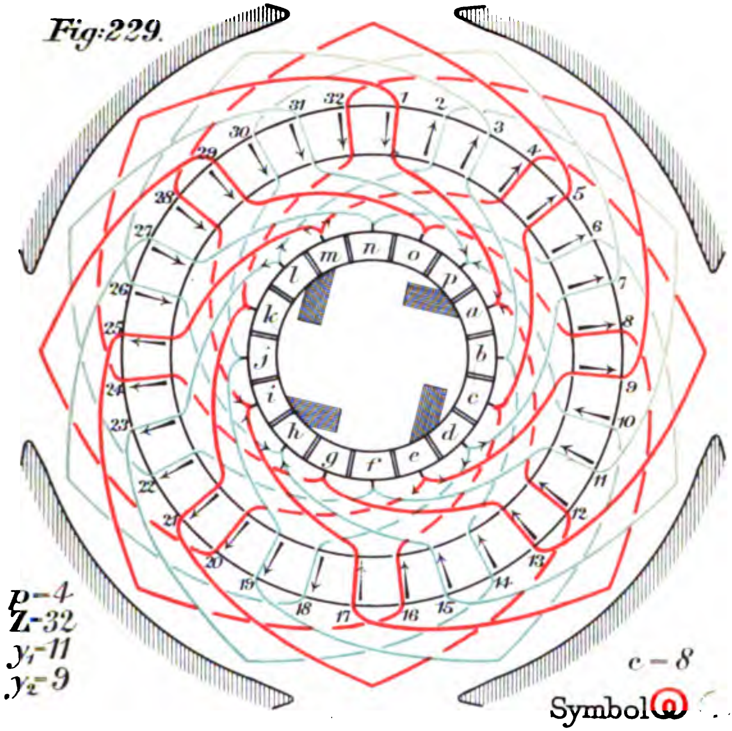
FOUR-CIRCUIT. DUPLEX, SINGLY RE-ENTRANT



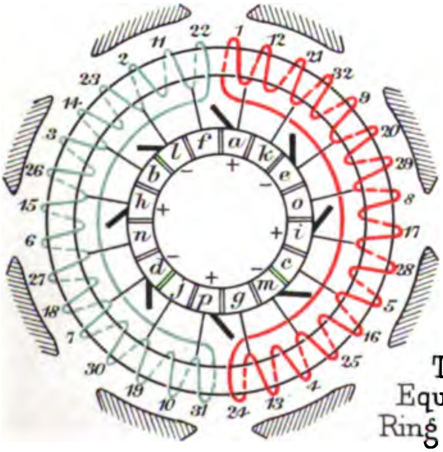
The Equivalent Ring Winding

E. & F. N. Spon Ltd London

Fig:229.



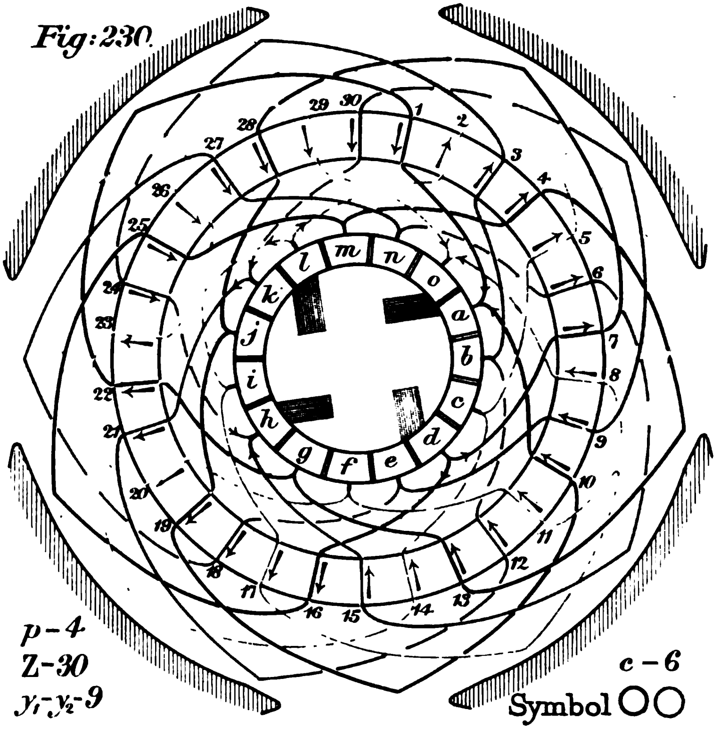
EIGHT-CIRCUIT. DUPLEX, DOUBLY RE-ENTRANT.



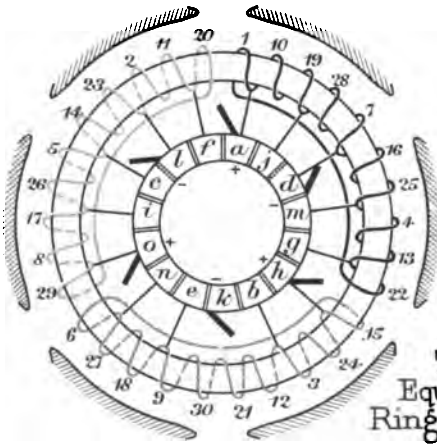
The Equivalent Ring Winding

Thos Kell & Son Lith

Fig: 230.



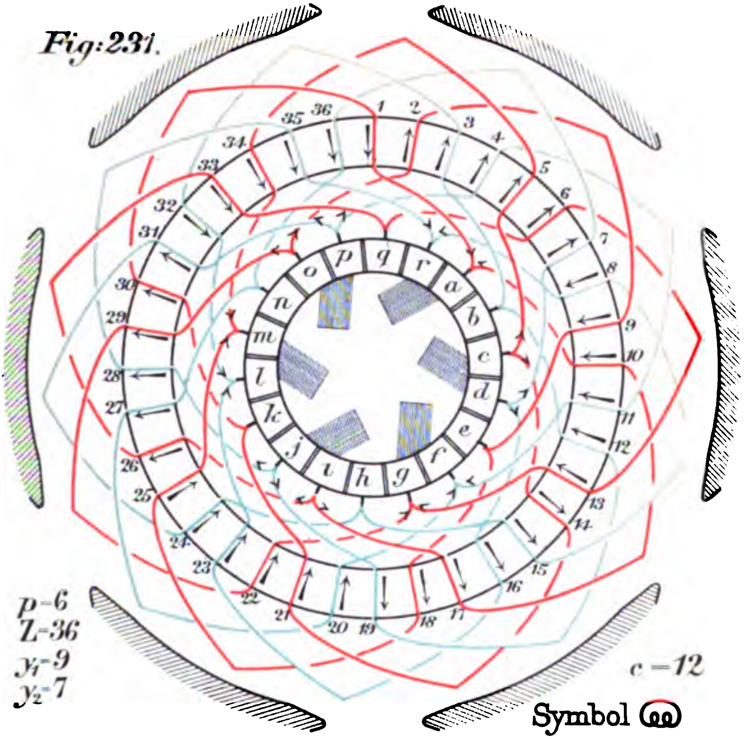
SIX-CIRCUIT. TRIPLEX, SINGLY RE-ENTRANT



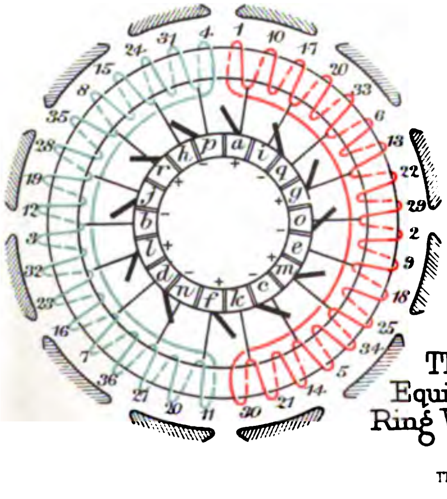
The Equivalent Ring Winding

E. & F. N Spon L^td London

Fig: 231.



TWELVE-CIRCUIT. DUPLEX, TREBLY RE-ENTRANT.



The Equivalent Ring Winding

Thos Kell & Son, Lith.

bet
col
re-
trij
res
cou

duc

du
req
equ
and

eac
dif
is
lat

se

Si
se
Tl
co
wl
pi
dc
se
ar
nc
of
co
ci
th

between $\frac{1}{2}$ Z and y, there will be three independent windings, coloured respectively red, green and black, and each is singly re-entrant, so that there are 6 circuits (symbol O O O). This triplex winding should be compared with Fig. 227, which also results in a six-circuit winding. The equivalent ring has, of course, also three independent windings.

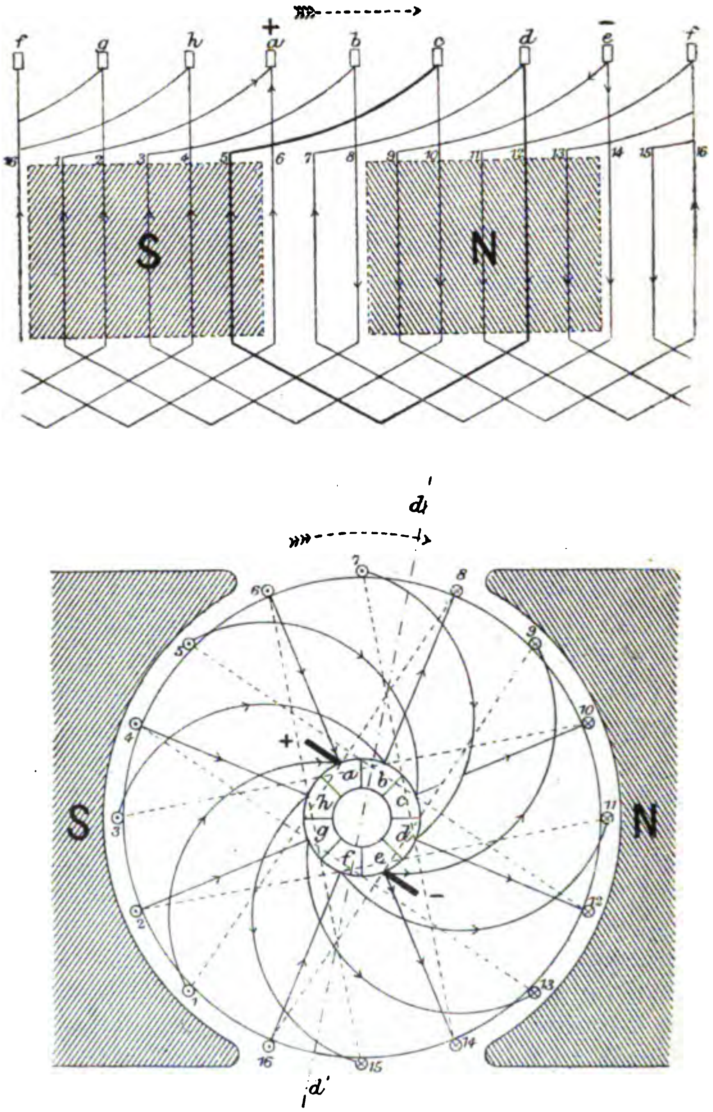
Fig. 231 is a 6-pole, twelve-circuit winding, with 36 conductors, and an average winding pitch of 8, resulting in a duplex trebly re-entrant winding (symbol). It requires but 6 broad brushes, though, as is obvious from the equivalent ring diagram, it has 12 circuits in parallel one with another.

It will be noted that Figs. 226 and 228 depict two cases in each of which there are 6 poles and 32 conductors. They differ, however, in the winding-pitch, with the result that one is a two-circuit and the other a four-circuit winding. The latter would yield double the current at half the voltage.

DRUM-WINDINGS.

As examples of windings the following may be of some service.

In Figs. 232 and 233 are given a right-handed winding on Siemens' plan for an 8-part commutator, and one turn to each section, *i.e.* with 16 conductors spaced round the periphery. The connecting pieces at the front end consist of straight connectors (such as *a* 6) and spiral connectors (such as *a* 1), which cross (either under or over) the former. The connecting pieces at the back end are not further indicated than by the dotted lines drawn across. In the developed diagram it is seen that each element of the winding is similar to *c*–5–12–*d* and that the arrangement is a lap-winding. The back connectors space over seven conductors, being just short by one of the number $\frac{1}{2}$ Z in the semi-circumference; whilst the front connectors space over five, being short by three of the semi-circumference, or $y_1 = 5, y_2 = -7$. It will be further noted that with this right-handed winding, rotating right-handedly in a right-handed field, the + brush is near the top of the commutator.



FIGS. 232 AND 233.—LAP-WINDING (SIEMENS' RIGHT-HANDED) DEVELOPMENT AND END VIEW.

Figs. 234 and 235 represent the same thing, except that the winding is left-handed, with the result that the + brush is now near the bottom of the commutator.

The winding table for both these figures is the same, namely :—

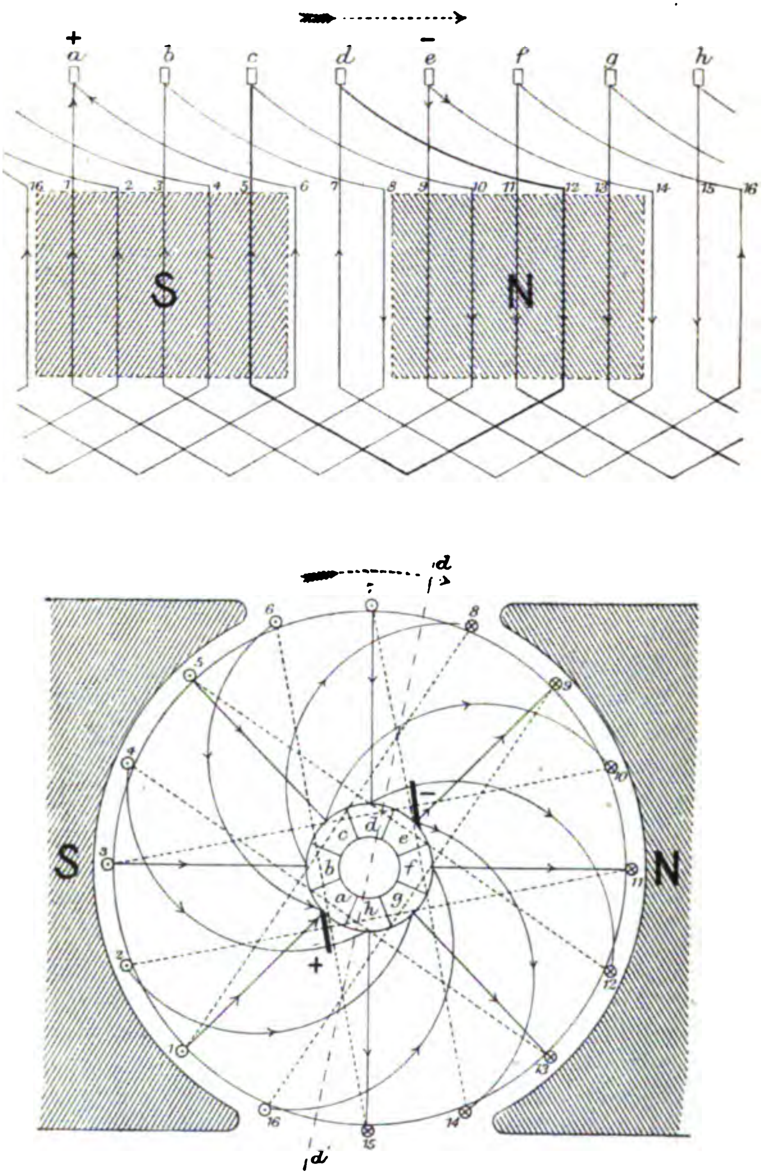
F	B		F
+ *a*	1	8	*b*
b	3	10	*c*
c	5	12	*d*
d	7	14	*e*
− *e*	9	16	*f*
f	11	2	*g*
g	13	4	*h*
h	15	6	*a*

But in the right-handed winding the spiral connectors, such as *a* to 1, go toward the left, and in the left-handed winding to the right.

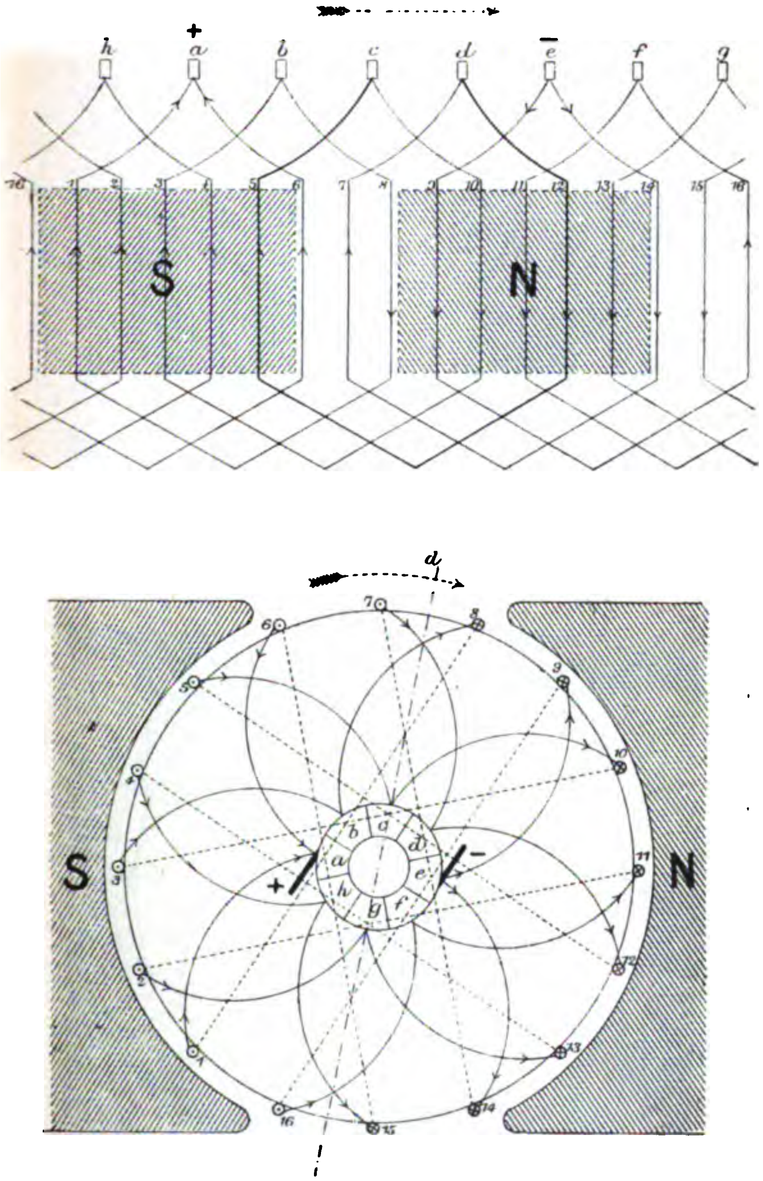
In Fig. 232 and Fig. 234 (the developments) it is seen that for both these windings the "element" of the winding, indicated by the darker lines, is unsymmetrical at the front connectors, one straight, one spiral, this being due to the use of two sorts of conductors. The bar *a* of the end of the drum commutator is connected to the front end of No. 1 and No. 6. In one case it is skewed forward to be opposite No. 6; in the other it is skewed backward to be opposite No. 1. Why should it not be placed symmetrically between them?

Figs. 236 and 237 depict a symmetrical lap-winding, electrically precisely equivalent to the preceding, and having the same winding table. The advantages are twofold: that for built-up armatures the connectors at the front end are now all of the same pattern, consisting of two sets of short spirals; and that the brushes now come to a horizontal diameter. The back connexions remain exactly as before, and go across a longer chord than the front connexions.

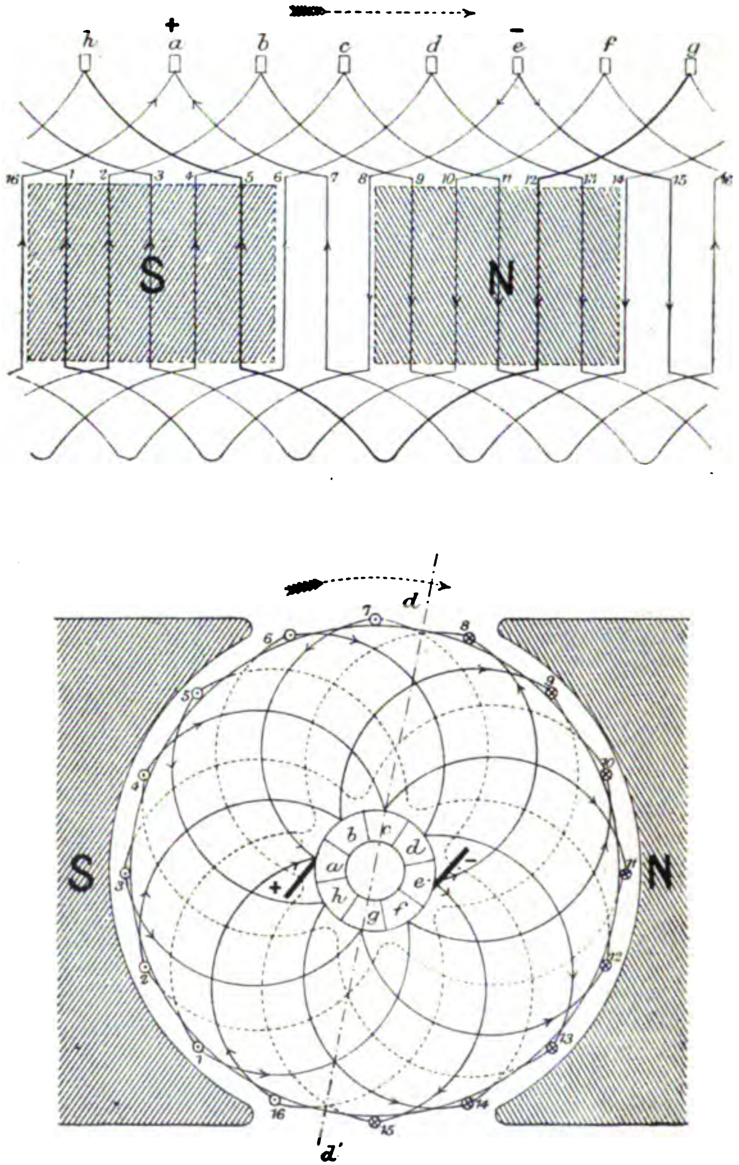
To secure the utmost symmetry in the winding, the back



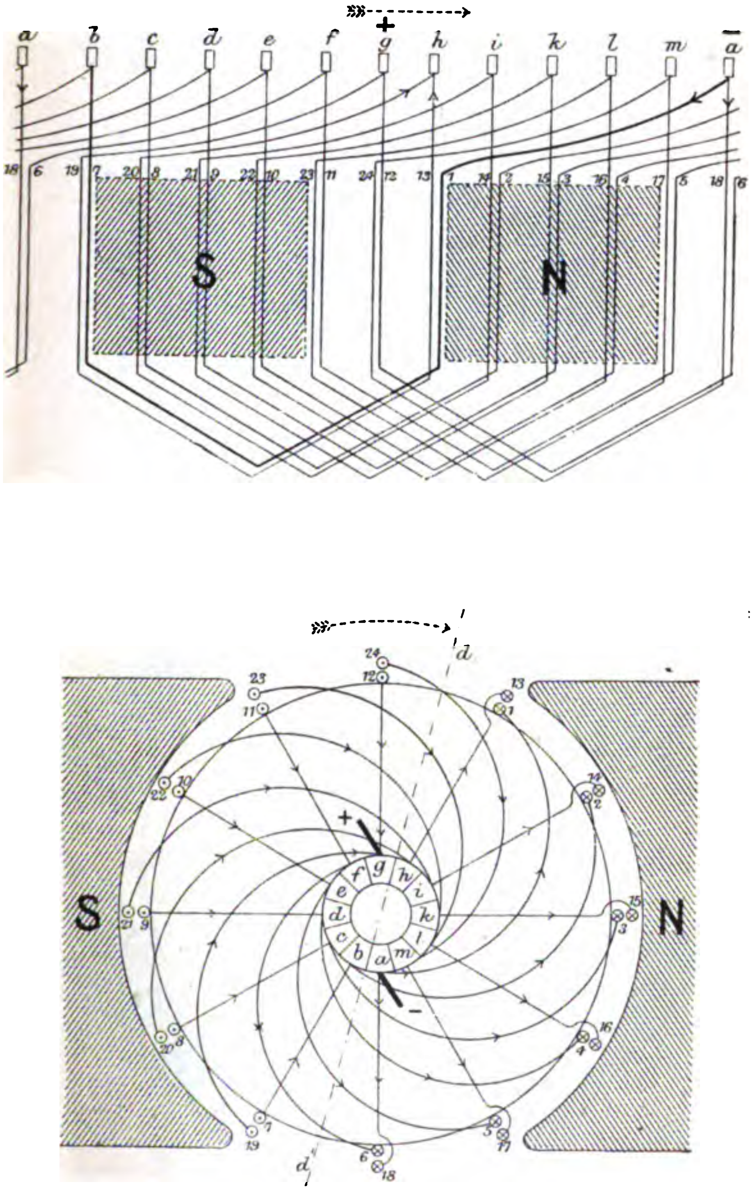
FIGS. 234 AND 235.—LAP-WINDING (SIEMENS' LEFT-HANDED) DEVELOPMENT AND END VIEW.



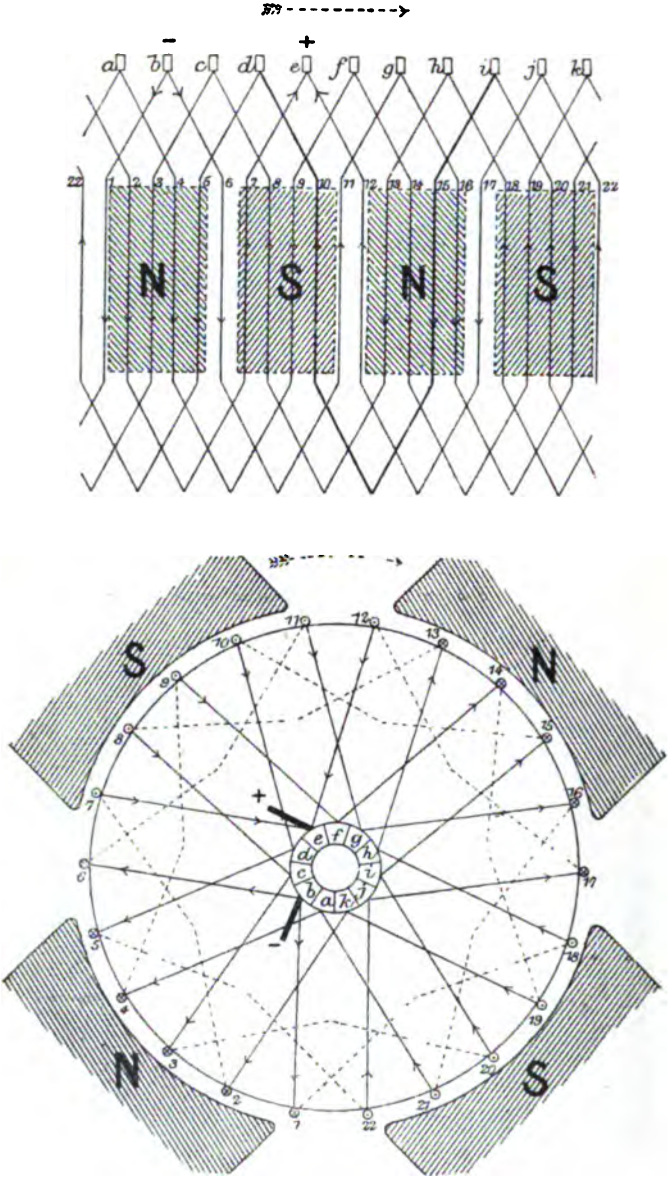
FIGS. 236 AND 237.—LAP-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.



FIGS. 238 AND 239.—WAVE-WINDING (2-POLE SYMMETRICAL) DEVELOPMENT AND END VIEW.

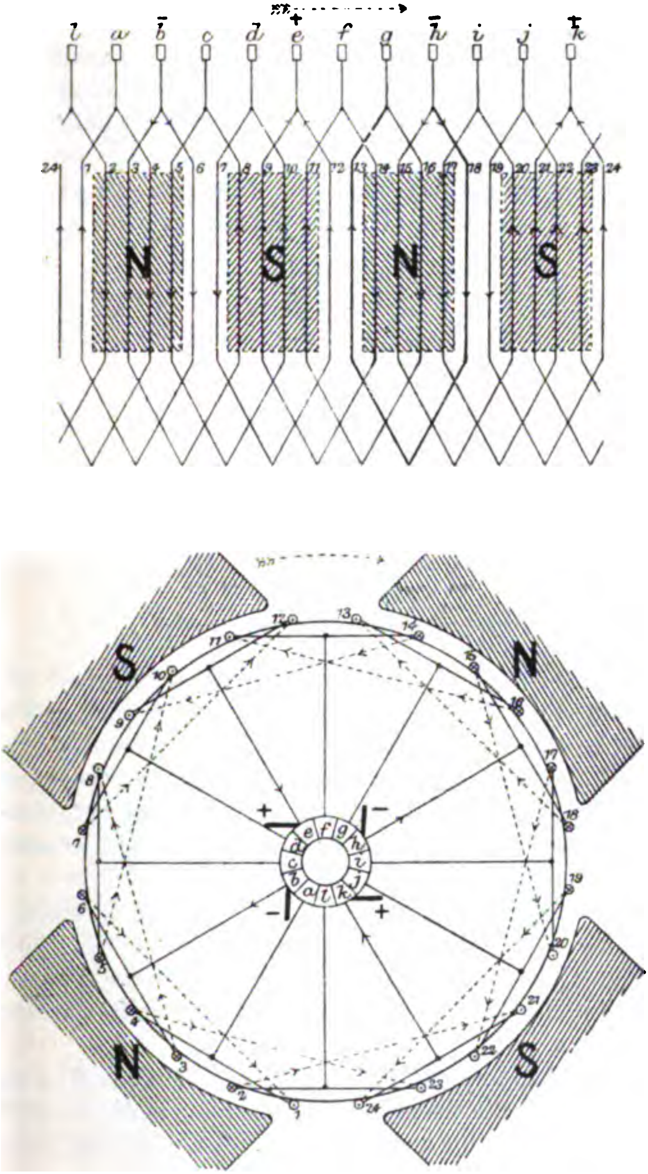


FIGS. 240 AND 241.—TWO-LAYER DRUM-WINDING.



FIGS. 242 AND 243.—DRUM-WINDING: SERIES GROUPING.

$Z = 22$; $y_1 = y_2 = 5$; $c = 2$.



FIGS. 244 AND 245.—THURY'S ARMATURE (4-POLE LAP-WINDING.)
$Z = 24$; $y_1 = 3$; $y_2 = -5$; $c = 4$.

and front connectors ought to be equalized. The theoretically proper spacing is $y_1 = 7, y_2 = 9$. To attain this, join No. 1 to No. 8 at one end of the drum and to No. 10 at the other. The result is shown in Figs. 238 and 239, from which it is at once apparent that we have passed from lap-windings to a wave-winding; each element passing around the drum and returning only to the next bar of the commutator from whence it started. The winding table for this case is :—

F	B		F
+ *a*	16	9	*b*
b	2	11	*c*
c	4	13	*d*
d	6	15	*e*
− *e*	8	1	*f*
f	10	3	*g*
g	12	5	*h*
h	14	7	*a*

Electrically this winding is the precise equivalent of the three preceding. The spiral connectors at the back end meet in pairs, as those at the front meet at the commutator.

A two layer winding for twenty-four conductors, together with its development, are given in Figs. 240 and 241, showing how, when half the armature, from *a* to *g*, has been completed one layer has been wound.

As mentioned on p. 411 below, the winding of multipolar armatures with series-grouping was suggested by Professor Perry.[1] It was applied to drum-winding by Messrs. Paris and Scott,[2] and by Mr. Kapp, and has come into extensive use in recent times.

In Figs. 242 and 243 are given the connexions for a 4-pole drum-winding with twenty-two conductors; here $y = 5$. The winding-table for this armature is as follows :—

---

[1] Specification of Patent, No. 3036 of 1882.

[2] Specification of Patent, No. 4683 of 1884.

4-POLE DRUM : 22 CONDUCTORS : SERIES GROUPING.

F		B		F		B		F
	D		U		D		U	
	1		18		13		8	
	3		20		15		10	
	5		22		17		12 +	
	+ 7		2		19		14	
	9		4		21		16	
	11		6	−	1			

In Figs. 244 and 245 is given a lap winding used by Thury (see Fig. 453, p. 716), the case illustrated being that of a 4-pole drum. It is a lap-winding for parallel grouping, with a spacing at the back end just short of the pitch of the poles and a still shorter spacing at the front end. This is a form of chord winding intended to keep conductors at very different potentials from overlapping, and it can be well insulated because the separate sections can be wound on formers before being laid over the core.

A method of drum winding was proposed by Fritsche,[1] in which the conductors all lie obliquely across the surface of the drum, no part of them being parallel to the shaft. In this case the field-magnet poles are also constructed with diagonal faces. The oblique winding is shown developed in Fig. 246; which should be compared with the winding of Fig. 216, p. 361, to which it is electrically equivalent.

Duplex and Multiplex Windings.—In dynamos intended to yield currents so large that a difficulty in commutation is likely to arise, it is convenient to have two or more distinct windings on the armature, each connected to its own set of commutator bars, all the sets being interleaved in one commutator and the current being collected by a pair of broad brushes or a set of several brushes connected together so as to virtually form one broad brush. The advantage of this method is that only a fraction of the whole current has to be reversed in the passing of any one bar of the commutator. The division of what would otherwise be very stout conductors into several smaller conductors, also has the effect of reducing eddy-current loss

---

[1] *Die Gleichstrom-Dynamomaschine*, Berlin, 1889.

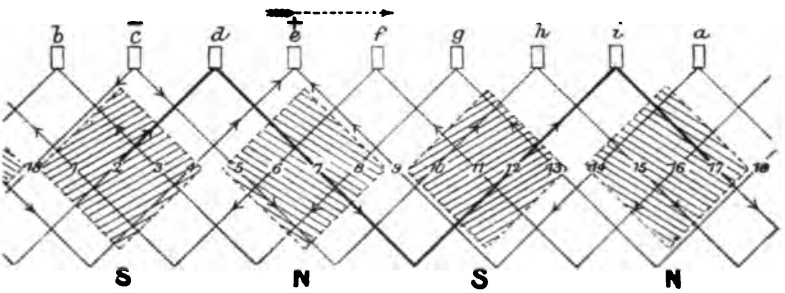
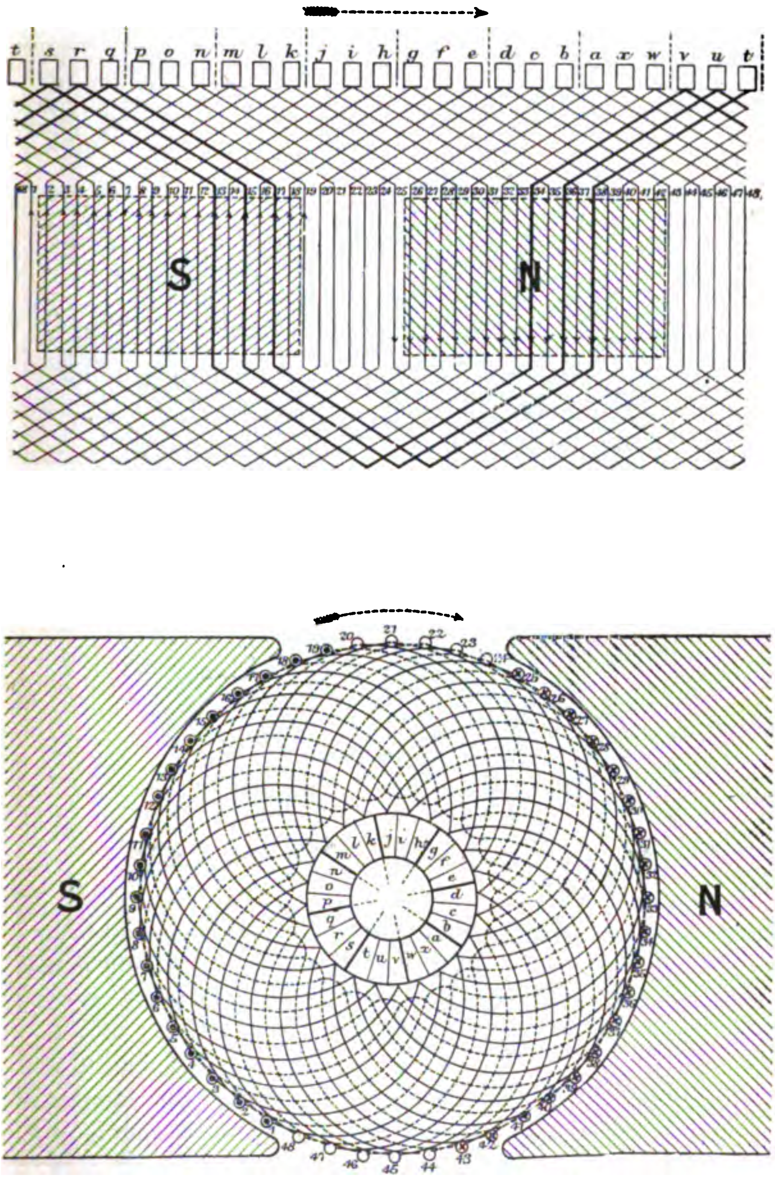


FIG. 246.—FRITSCHE'S OBLIQUE WAVE-WINDING.

Figs. 247 and 248 show the connexions of a triplex-wound drum armature for a 2-pole field having 48 conductors in all, that is to say, 16 in each independent circuit. In practice a greater number of conductors would of course be used. Each circuit is wound as an ordinary drum-winding, being con-

CIRCUIT *a*.				CIRCUIT *b*.				CIRCUIT *c*.			
F	B		F	F	B		F	F	B		F
a	1	22	*d*	*b*	47	20	*e*	*c*	45	18	*f*
d	43	16	*g*	*e*	41	14	*h*	*f*	39	12	*i*
g	37	10	*j*	*h*	35	8	*k*	*i*	33	6	*l*
j	31	4	*m*	*k*	29	2	*n*	*l*	27	48	*o*
m	25	46	*p*	*n*	23	44	*q*	*o*	21	42	*r*
p	19	40	*s*	*q*	17	38	*t*	*r*	15	36	*u*
s	13	34	*v*	*t*	11	32	*w*	*u*	9	30	*x*
v	7	28	*a*	*w*	5	26	*b*	*x*	3	24	*c*



FIGS. 247 AND 248.—TRIPLEX-WOUND 2-POLE DRUM ARMATURE.

nected to 8 bars of the commutator. There are no connexions between the three circuits except such as are made by the brushes, which are broad enough to overlap three bars of the commutator, thus putting the three circuits in parallel.

The winding-tables for this armature are given on p. 398.

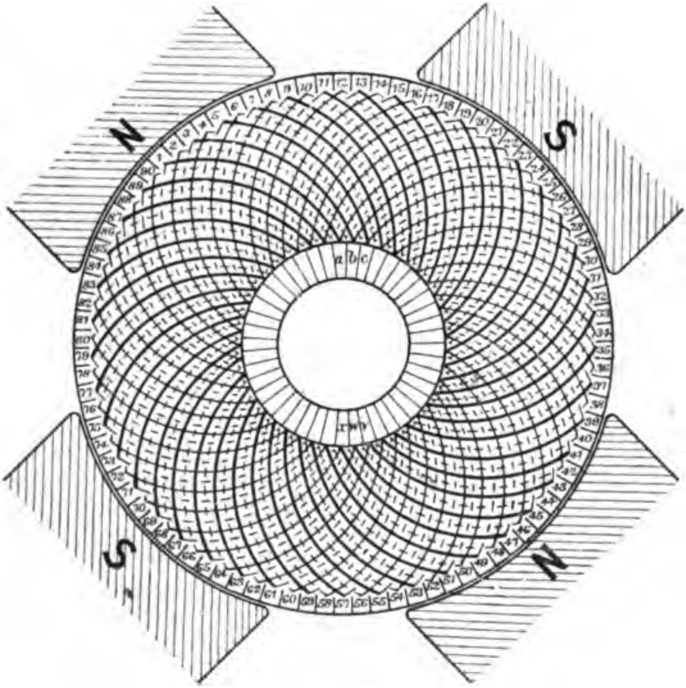
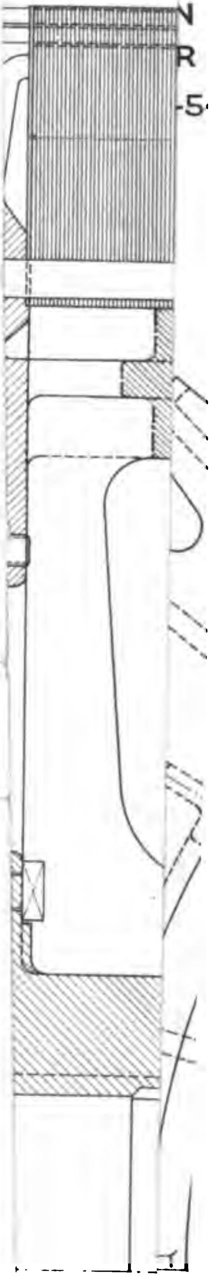


FIG. 249.—TRIPLEX-WOUND 4-POLE DRUM ARMATURE.

Fig. 249 shows the connexions of a triplex-wound drum-armature for a 4-pole field. The connexions are sufficiently clear without the aid of a winding-table. There are 90 conductors, 30 in each circuit, the spacing being 21.

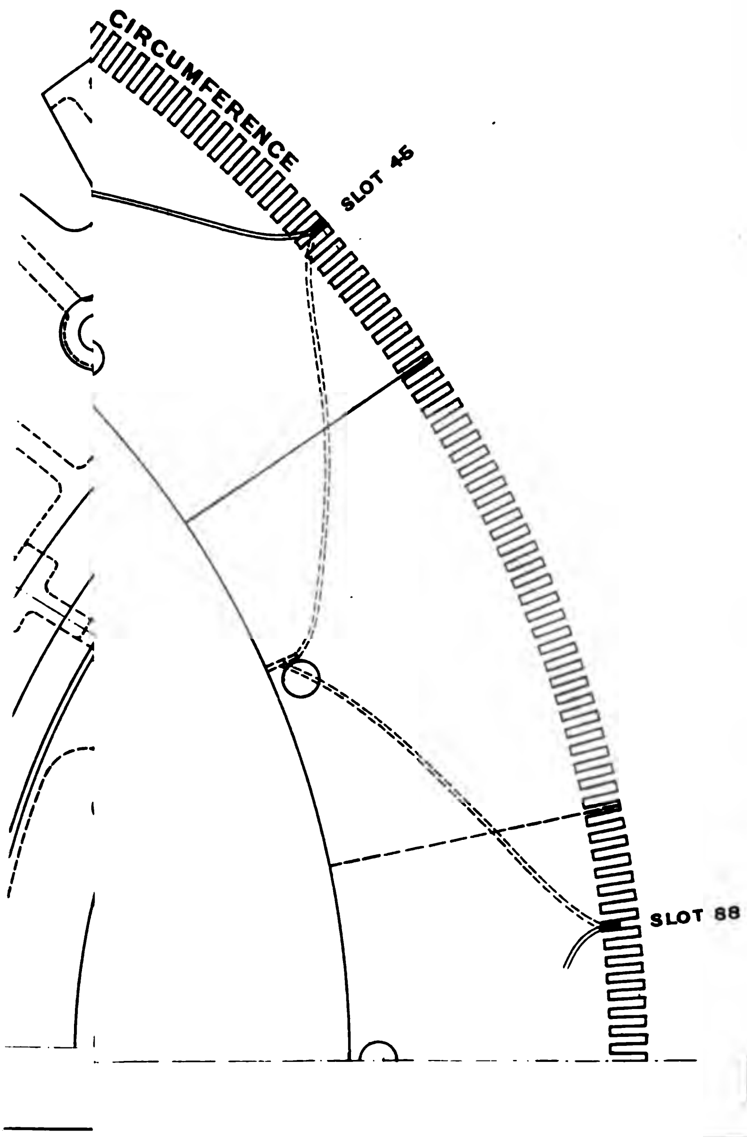
Further Examples of Drum-Windings.—An example of a lap-winding is afforded by the 6-pole Scott and Mountain generator, page 582, in which $Z = 496$, $K = 248$. $g = 2$, $c = 6$, $y_1 = 41$, $y_2 = -39$, $y = 2$, the conductors lying in 124 slots, 4 conductors per slot. As there are 6 poles there are $20\frac{2}{3}$



Spo

OF

A



London

Thos Kell & Son Lith

slots per pole. The coils are grouped to span over 20 slots, conductor No. 1 (upper) in No. 1 (Fig. 250) slot being united to conductor No. 2 (lower) in No. 21 slot; and No. 2 in No. 21 slot is connected back to No. 3 (upper) in No. 1 slot, which in turn is joined to No. 4 (lower) in No. 21 slot, as shown in Fig. 250. This is then returned to No. 1 (upper) in No. 2 slot, and so forth. If the conductors were numbered consecutively, beginning with No. 1, in No. 1 slot, those in No. 21 slot would become Nos. 41, 42, 43 and 44. Hence if No. 1 is joined at the front end to No. 42, and No. 42 at its back end laps back to No. 3, the pitches are respectively $y_1 = 41, y_2 = -39$, and $y = 2$. This is therefore a simplex singly re-entrant winding.

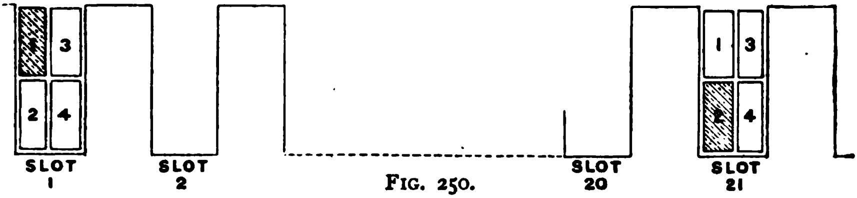


FIG. 250.

As an example of a wave-winding we may take the 10-pole generator of Kolben (p. 671 and Plate XVII.). This has 874 conductors lying in 437 slots, *i.e.* two conductors per slot. Now $874 = 87 \times 10 + 4$. Hence if $y = 87$, it follows that $c = 4$, and the winding will be doubly re-entrant, or is a series-parallel winding. The winding table may be constructed as follows, beginning with conductor No. 1 :—

1st round . . .	1	88	175	262	349	436	523	610	697	784	871
2nd round . . .	871	84	171	258	345	432	519	604	693	780	867
3rd round . . .	867	80	167	254	341	428	515	600	689	776	863
. . . .											
44th round . . .	703	790	3	90	177	264	351	438	525	612	699
45th round . . .	699	786	873	86	173	260	347	434	521	608	695
. . . .											
87th round . . .	531	618	705	792	5	92	179	266	353	440	527
88th round . . .	527	614	701	788	1						

The winding becomes re-entrant after 87 rounds plus 4 steps. It had become all but re-entrant by returning to No. 3 (instead of No. 1) after 44 rounds plus 2 steps.

Mixed Wave and Lap-Winding.—None of the foregoing formulæ take any account of certain symmetrical windings in practical use which are mixed. Fig. 251 is a simple example of such a winding, essentially a wave-winding, of which each element consists of 4 loops in series. Windings of this general

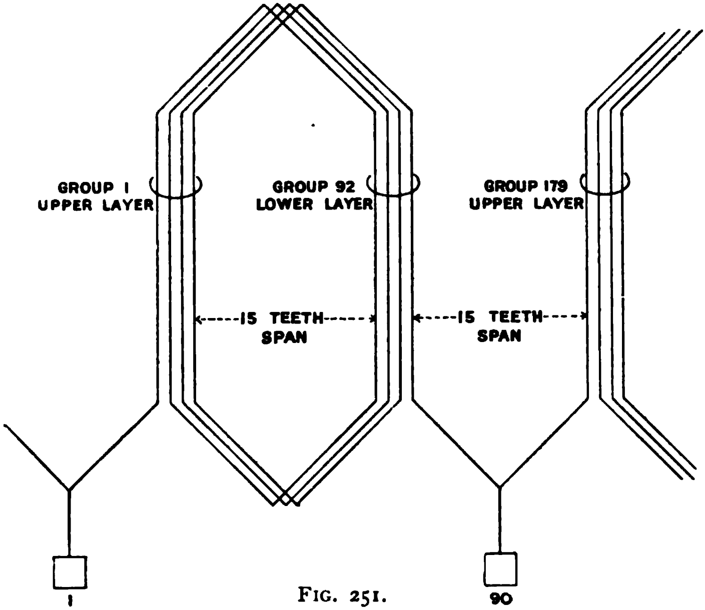


FIG. 251.

character lend themselves to small or medium sized armatures with former-wound coils, as those of tramway motors, or for special high-voltage construction. An example is to be found in the high-voltage 4-pole dynamo of Messrs. Brown, Boveri & Co., Fig. 479. This is a winding of great interest. There are 59 slots, receiving 59 former-wound groups of coils. Each group is made up of three separate "sections," so that the number of "sections" is 177, and there are 177 segments to the commutator. These sections are connected up as a wave-winding. But each section itself consists of 4 loops or turns.

There are therefore 24 wires through each slot, making 1316 conductors in all. They may be regarded as 177 "sections," each consisting of 8 conductors united together; or, for purposes of calculation we may regard the whole thing as a wave-winding of 354 conductors, and then substitute 8 conductors for the 2 in each loop. Now to make a singly re-entrant wave-winding of 354 conductors we must have an average pitch $\bar{y}$ such that $p\bar{y} \pm 2 = 354$; whence $\bar{y} = 89$ or 88. As a matter of fact the average pitch chosen is 89, and the two actual pitches are $y_1 = 87, y_2 = 91$, the winding table being as follows :—

First round $$1 \underset{91}{—} 92 \underset{87}{—} 179 \underset{91}{—} 270 \underset{87}{—} 3$$

Second round $$3 \underset{91}{—} 94 \underset{87}{—} 181 \underset{91}{—} 272 \underset{87}{—} 5$$

and so forth. But the steps of pitch 91 are all of them laps of 4 turns, while the steps of pitch 87 are mere connexions down to the commutator and then on to the next set of 4 turns in the succession, as in the following scheme :—

Groups Upper	1		179		3		181		5		182		etc.
Groups Lower		92		270		94		272		96		274	
Commutator Bar	1	90		2		91		3		92		4	

Now as there are 354 "groups" in 59 slots this is 6 "groups" per slot, three "upper" of odd number and three "lower" of even number. As there are 6 in a slot we may take

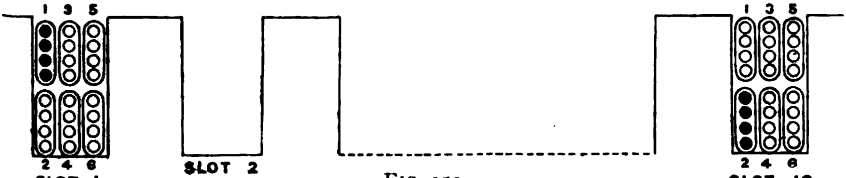


FIG. 252.

No. 1 slot as containing groups 1 to 6, No. 2 slot groups 7 to 12, and so forth, so that No. 16 slot will contain 91 to 96.

Then group 92 will be the first lower group in No. 16 slots, and the slot-pitch for the former-wound coils will be from No. 1 slot to No. 16 slot, or the slot-pitch for the coils spans over 15 teeth.

Number of Brush-sets.—The number of places on the commutator at which it is necessary or advisable to place a set of collecting brushes can be ascertained from the winding diagrams. All that is necessary is to draw arrows marking the directions of the induced electromotive-forces. This has been done, for example, in the radial diagrams Figs. 217 to 245. Wherever two arrow-heads meet at any segment of the commutator there a positive brush is to be placed: and at every point from which two arrows start in opposed directions along the winding, there is the place for a negative brush.

For all *lap-windings*, and for ordinary *parallel ring-windings*, there will be as many brush-sets as poles, and they will be situated symmetrically around the commutator in regular alternation, + and −, at angular distances apart equal to the pole-pitch. It must be remembered that the number of brush-sets does not necessarily show the number of circuits through the armature. Take the case of a 4-pole machine with four sets of brushes at 90° apart from one another. If the winding is a simplex, singly re-entrant lap-winding, there will be 4 circuits. But if the winding is a duplex, or a doubly re-entrant lap-winding there will be 8 paths. If a triplex singly re-entrant lap-winding there will be 12 circuits. An ordinary ring placed in a multipolar field would have as many neutral points on its commutator as there are poles around it, and would therefore need as many brushes as the machine had poles. In Plate XXV. are given two views of the large Berlin type of multipolar ring machines with internal field-magnets, which originated with Messrs. Siemens and Halske. The ring-winding is built up of separate copper conductors which are joined together in a simple continuous spiral. The outer portions of these conductors are made deep and broad, so as to serve as a commutator. The brushes trail on the outer surface of the ring; and it will be noted that there are as many sets of brushes as there are internal poles; the brushes are spaced out at equal angular distances; there being 10 sets of them, alternately positive and negative. The 5 positive brushes are all connected together electrically; while the 5 negative brushes are also connected together. In this case there are 10 paths through the armature from the + to the – side of the circuit.

For *wave-windings*, whether series or series-parallel, and for series ring-windings, if the arrow-heads are similarly drawn it will be found that there are required but two brush-sets, whatever the number of poles; and the angle between the + set and the – set will be the same as the angle between any N-pole and any S-pole. Thus for a 10-pole machine with wave-wound armature, the brush-sets may be 36° apart, or they may be $3 \times 36° = 108°$, or $5 \times 36° = 180°$ apart. But it must again be remembered that though there *may* be only two brush-sets, the number of circuits through the winding is not necessarily 2. For if the winding is duplex or if it is doubly re-entrant, the number of circuits will be 4. If both duplex and doubly re-entrant 8.

There are, however, some further considerations that deserve attention.

Reduction in Number of Brush-sets.—Cases occur when it may be desirable, with a parallel-winding (for which the number of brush-sets would naturally be equal to the number of poles), to reduce the number of brush-sets. In the case of 4-pole tramway motors mere convenience of access dictates the reduction of the number of brush-sets to 2. Now, if a wave-winding is adopted the number will naturally be 2, not 4. If a parallel winding is adopted the number 4 may be reduced to 2 by the application of Mordey's device of cross-connecting the segments of the commutator. Let us, however, consider what is the result, without resorting to either of these expedients, of simply using, with a parallel-wound 4-pole armature, 2 brushes instead of 4. Suppose the machines to be generating 120 amperes; then if 4 brushes are used there will be 4 circuits, each carrying 30 amperes, and at each "brush" the current will be 60 amperes (Fig. 253). If now

2 of the brushes are removed, and the dynamo still generates 120 amperes, the current through each of the two remaining brushes will be 120 amperes; while internally there will be only 2 circuits. But these will not take equal shares of the current, since, though the sum of the electromotive-force in each circuit is the same, the resistance of one is three times that of the other. So the currents will be about 90 amperes in one circuit, and about 30 amperes in the other as in Fig. 254. Assuming that no spark-difficulties occur in collecting 120 amperes at either brush the arrangement will work perfectly.

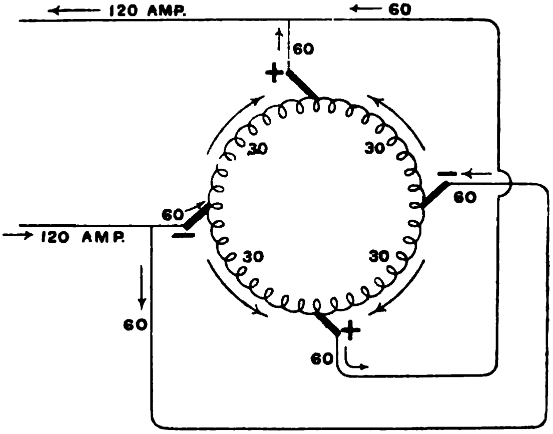


FIG. 253.

But the heat losses will be greater than before. For, if the resistance of one-quarter of the winding be taken as 0·05 ohm, the heat loss will be:—

With 4 brushes $4 \times 30 \times 30 \times 0{\cdot}05 = 180$ watts.

With 2 brushes $\left\{\begin{array}{l} 1 \times 90 \times 90 \times 0{\cdot}05 \\ 3 \times 30 \times 30 \times 0{\cdot}05 \end{array}\right\} = 540$ watts.

It is not an uncommon thing in the case of 6-pole slow speed exciter machines to see only 4 brush sets instead of 6.

Increase in Number of Brush-sets.—In cases where wave-windings are used, requiring, as we have seen, only two brush-sets, it is often advisable to use *more* sets than two. This is particularly the case where the current to be collected is several hundred amperes. In fact, though in one sense only two sets are required, and these situated at an angular distance apart equal to the angular distance from one N-pole to any S-pole, there is no harm done if as many sets are employed as there are poles. Consider a singly re-entrant simplex wave-winding for an 8-pole machine such as Fig. 223. Whenever any brush bridges across between two adjacent bars of the commutator it short-circuits one "round" of the wave-winding, and this "round" is connected at three intermediate points to other bars of the commutator. So, if the short-circuiting brush is a + brush, no harm will be done by three other + brushes touching at the other points. If these other brushes are broad enough to bridge across two commutator bars, then they may have the effect that commutation may go on at them also, three "rounds" instead of one undergoing commutation together. Or, what amounts to the same thing, the duration of act of commutation for any one "round" will be prolonged, much as it would be if for the one brush there were simply substituted one of greater breadth. Certain it is that the commutation is in general improved by using more brush-sets than two. Many makers of multipolar machines with wave-windings, habitually use the full number all round the commutator. As examples, see the Kolben 10-pole machine, p. 671, and the Oerlikon 12-pole machine, p. 656.

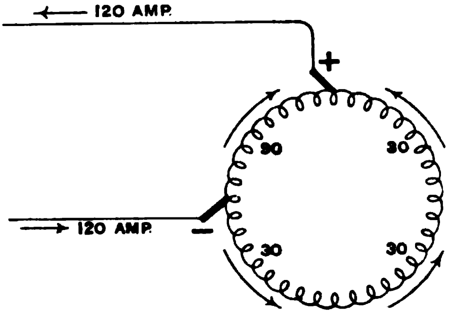


FIG. 254.

Choice of Number of Circuits.—From the considerations already discussed it will be seen that it is possible to have windings that give any desired (even) number of circuits in machines having any number of poles. It was not known until recent years that this could be so ; that, for example, one might have a 6-pole machine with 4 circuits, or an 8-pole machine with 6 circuits. A few considerations on the choice of alternatives may be desirable. In large multipolar generators it is as a rule inadvisable to have more than 100 or 150 amperes in any one circuit. [Special machines for electrochemical work form exceptions.] Suppose then it were desired to design a 6-pole machine to give an output of 400 amperes. If designed with 2 circuits as a singly re-entrant wave-winding, there would be 200 amperes per circuit. If with a duplex singly re-entrant wave-winding, or a simplex doubly re-entrant wave-winding, there would be 4 circuits each carrying 100 amperes. If with a triplex singly re-entrant wave-winding, or with a parallel lap-winding, 6 circuits with 66·6 amperes each. In each case except the last there might be only 2 brush-sets ; but in each case 6 brush-sets would be preferable. From this last point of view there is nothing to choose. But the 2-circuit winding is too thick, and the 6-circuit winding involves an unnecessarily great number of conductors and connexions. The 4-circuit winding is distinctly preferable. Again, suppose a 12-pole slow-speed machine were desired for a high voltage and to give out 300 amperes. A parallel winding with 12 circuits each carrying only 25 amperes would be absurd: a 2-circuit winding would be distinctly preferable.

Thus it will be seen that wave-windings, with their many possibilities of different groupings in series, series-parallel, etc., offer distinct advantages over lap-windings, and they possess the further incidental advantages of equalizing any inequality in the magnetic fields of the various poles, and, in general, of requiring fewer conductors and end-connexions than lap-windings do. Arnold has given the following very striking example of the adaptations of wave-winding:—

Taking the formula (p. 380) for series parallel grouping $y_{k_1} = \frac{2K \pm c}{p}$, and applying it to the case of a 6-pole machine with 290 conductors and 145 commutator bars, we may have with one and the same size of core-disk, and the same size of conductors, the following cases:—

No. of Circuits.	Winding Step at Commutator.	Volts.	Amperes.
2	48	250	100
4	49	125	200
8	47	62·5	400
10	50	50	500

With the same core-disk, a doubly re-entrant lap-winding would give:—

12	2	43	600

A disadvantage of series-groupings is, that in general they require an odd number of slots, making construction of the disks in segments a not too easy matter, unless the number of slots is divisible by 9, 15, or 21. Some makers find commutation less satisfactory in these machines than in those with parallel grouping.

Cross-Connexions. — It was noted above, that if for any reason the poles are of unequal strength, parallel-windings, whether lap-wound or ring-wound, work unequally, the current no longer dividing itself equally between the various circuits that are in parallel. As a result the heating is no longer a minimum. To mitigate this evil it is now customary to provide parallel-wound armatures with *equalizing connexions*, which are cross-connexions between those parts of the winding which are, or ought to be, at equal potentials.

As a matter of history such cross-connexions were introduced many years ago for other reasons.

In Fig. 255 is represented a mode of reducing the number of brushes to two, by cross-connecting windings at opposite sides of the ring, a device due to Mr. Mordey. This may be looked upon as simply putting into parallel with one another each coil and the one that occupies the similar place opposite the corresponding pole. The arrangement looks unsymmetrical, but is not really so. For a 6-pole machine each coil would need to be connected with the two others at 120°

on either side of it. There are several actual ways of doing this. One is by means of spiral connectors; another is by connecting across the corresponding bars of the commutator.

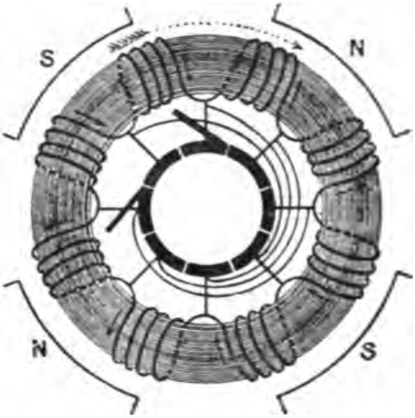


FIG. 255.—MORDEY'S METHOD OF MULTIPOLAR CONNEXIONS OF RING (PARALLEL CONNEXIONS).

In the Victoria (Mordey) dynamos of the Brush Company the length of shaft between the ring and the commutator permits

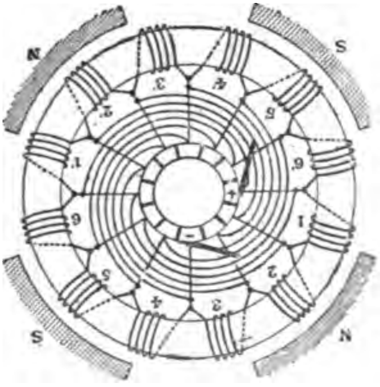


FIG. 256.—CONNEXIONS OF VICTORIA (MORDEY) 4-POLE ARMATURES.

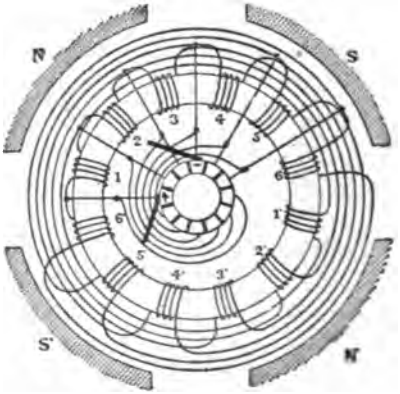


FIG. 257.—4-POLE RING, SERIES GROUPING (2 CIRCUITS).

of double cross-connexion, each junction of two adjacent sections being connected by a wire down to the nearest bar of the commutator, and also connected round to that on the opposite side, as in Fig. 256. Such cross-connected machines really have four collecting points on the commutator, but if brushes are placed at two only of these, they can still collect the current. Yet it is better to place brushes at all four points.

Special Groupings.—There are several methods of grouping the winding in series so as to gain a double electromotive-force. One of these modes, electrically symmetrical, is depicted in Fig. 257, wherein, while opposite coils are coupled in series, the commutator bars are cross-connected. This requires also but two brushes, at 90° apart. Two other modes of accomplishing the same end are shown in the windings of Figs. 258 and 259. Here, however, the connexions are not symmetrical, so that the resistances of the two paths (and therefore the respective currents) cannot be at all instants equal.

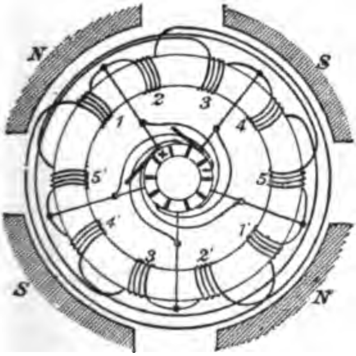


FIG. 258.—4-POLE RING, SERIES GROUPING (2 CIRCUITS).

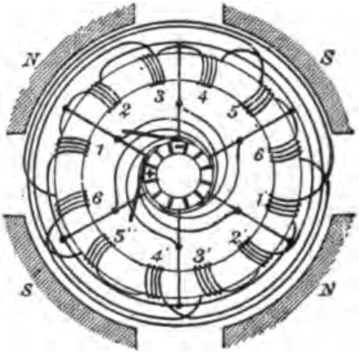


FIG. 259.—4-POLE RING, SERIES GROUPING (2 CIRCUITS).

In yet another arrangement (Fig. 260), each coil is connected down to q segments at intervals of $360° \div q$ around the ring; and introduces an increased number of bars of the commutator. This device of interpolating segments of the commutator is applicable to many machines.

Another winding, Fig. 261, devised by Professor Perry, brings down the connexions from each section across a chord of the commutator. The case shown is that of a ring with eleven sections in a 4-pole field. The number of sections and of parts of the commutator must be odd if the number of pairs of poles is even. It may be either odd or even for 6-pole or 10-pole machines. This is, in fact, a sort of wave-winding, carried out with ring elements. It is subject to the rules given on p. 381.

A further example is afforded by a special ring-winding used by Wodicka, Fig. 262, in which each section is joined in series with one on the side opposite to it, so that the number of commutator bars is half that of the sections. Here each "element" of the winding consists of two sections each containing active conductors; hence $p = 2$; $Z = 32$; $g = 2$; $y_1 = +15$; $y_2 = -11$.

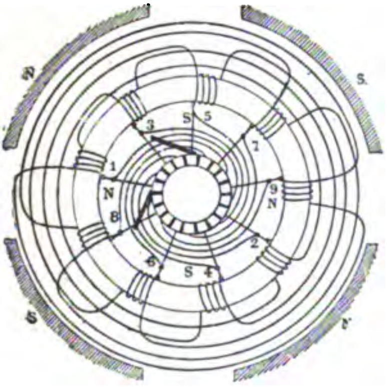


FIG. 260.—MULTIPOLAR RING, WITH INTERPOLATED SEGMENTS.

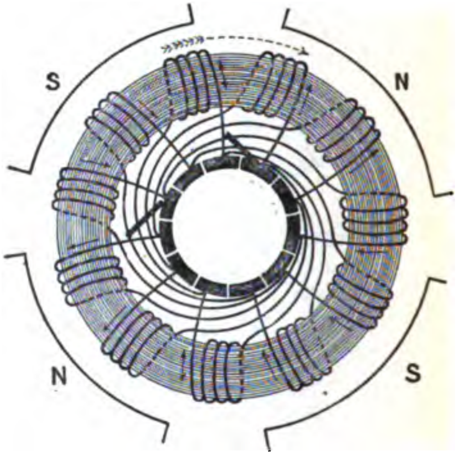


FIG. 261.—PERRY'S METHOD OF MULTIPOLAR SERIES GROUPING.

Equalizing Rings.—Equalizing connexions for the express purpose of equalizing the amounts of current collected at the various sets of brushes may be made in various ways. In multipolar machines, any two or more points in the winding that are during the rotation at nearly equal potentials may be connected together. If there were perfect symmetry in the field system no currents would flow along such connectors; but, owing to imperfect symmetry the induction in the various sections of the winding may be unequal and the currents not equally distributed. Thus in a 10-pole machine with parallel winding, suppose two of the poles to be badly excited owing to some defect of the exciting bobbins, then the sections of the armature winding as they pass those poles will not generate the full electromotive-force, and

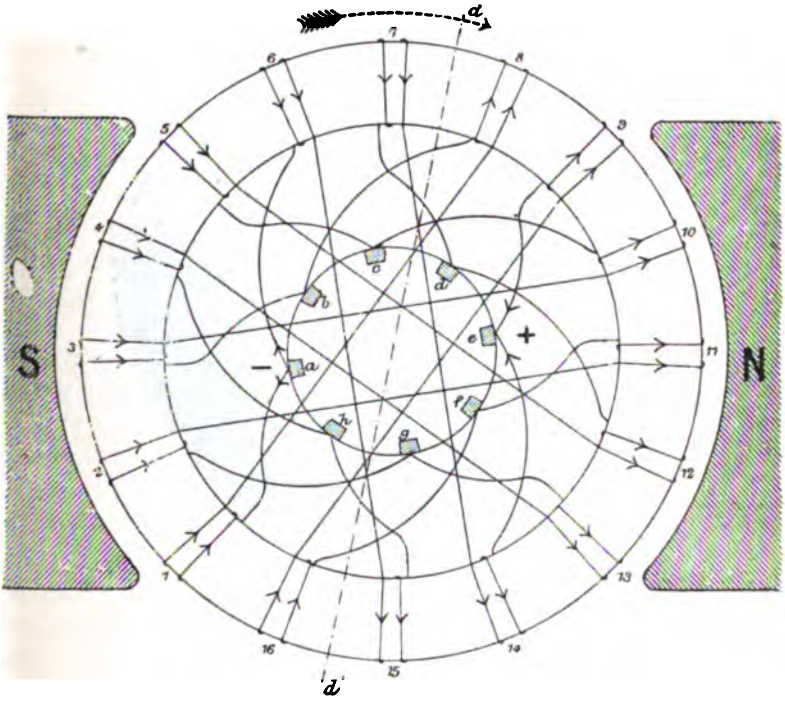


FIG. 262.—RING-WINDING WITH OPPOSITE COILS IN SERIES.

at this instant there will be an abnormal amount of current drawn from the other sections, tending to set up sparking. If now there are chosen 5 equidistant points on the winding and these are joined together by a connexion of low resistance, by being united to a copper ring, this adjunct will, at those instants when these five points are near the commutation-points, tend to equalize the distribution of current. But to be effective several such equalizing rings are needed, each independent of the other, and each connected down to the winding at points spaced out at distances apart equal to twice the pole-pitch.

As an example, suppose a 10-pole machine having $Z = 480$, with a parallel lap-winding, and that we decide to have 8

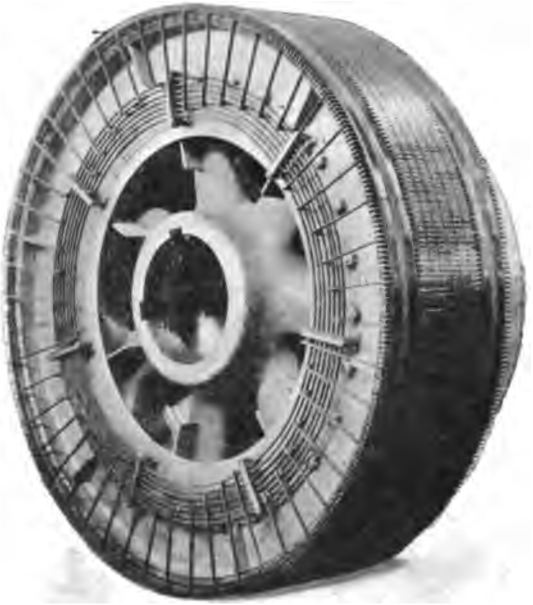


FIG. 263.—ARMATURE WITH EQUALIZING RINGS.

equalizing rings. As there are 96 conductors within the double-pole pitch, any conductor (No. 1 for example) will be joined to the 96th beyond it, and so on around the first ring. As there are to be 8 rings, if the first ring is joined to conductor No. 1, the next ring must be joined to the conductor that is the eighth part of the distance along the winding from No. 1 towards No. 97, that is to a conductor 12 places further on, namely No. 13, and so forth. Then the connexions to the rings may be tabulated like a winding-table as follows :—

First ring	1	97	193	289	385
Second ring	13	109	205	301	397
Third ring	25	121	217	313	409
Fourth ring	37	133	229	325	421
Fifth ring	49	145	241	337	433
Sixth ring	61	157	253	349	445
Seventh ring . . .	73	169	265	361	457
Eighth ring	85	181	277	373	469

It will be obvious that it is expedient for perfect symmetry that in designing an armature to be furnished with equalizing rings, Z should be chosen such that the number of rings and the number of poles are both of them factors of Z. In the case of double-current machines (see as example, Fig. 423) with connexions to yield three-phase currents, such three-phase connectors serve as equalizers even though no three-phase current is being drawn from the armature. Fig. 263 shows such equalizing rings in an armature of the Thomson-Houston Co. They are sometimes arranged at the back of the armature (see the machine of the English Electric Company, Fig. 301), or sometimes inside the commutator, or at the back of it (see the Scott and Mountain machine, Fig. 396). In some cases they are placed over the armature periphery like binding wires. The theory of equalizing connexions has been treated very fully by Arnold.[1] In order to discuss the application of equalizing connexions to wave-windings, he has suggested an ingenious "reduced scheme" or diagram in which he takes the various numbered sections of a wave-winding and rearranges them like a two-pole ring winding having equivalent properties. This is best understood by comparing Figs. 226 to 231, each of which represents a wave-winding together with the "reduced diagram" of the same winding. When such diagrams are made for 4-circuit or 6-circuit windings, it at once becomes obvious which coils are or ought to be equipotential, and the points to be joined by equalizing connexions can be seen. Arnold has patented equalizing connexions in wave-windings. One difficulty, namely that wave-windings require odd numbers of slots, giving rise to unbalanced groupings that are unsymmetrical, Arnold purposes to obviate by interpolating a single lap in the wave-winding in any section which has one element too few.

---

[1] *Elektrotech. Zeitschr.* xxiii. 215–220 and 233–235, 1902; and in his work *Gleichstrom-Maschinen* (1902).

To remedy inequality of poles in series windings, Mr. B. G. Lamme, of Pittsburg, has devised [1] the method of laying in the same slots a separate closed winding of low resistance connected down at symmetrical points, like the ordinary equalizing connexions, to two or more insulated rings. This virtually makes a parallel-connected polyphase closed winding, in which, unless the inductive actions are unequal, there will be no currents; but in which if the inductive actions of the individual poles are unequal, balancing currents will be induced.

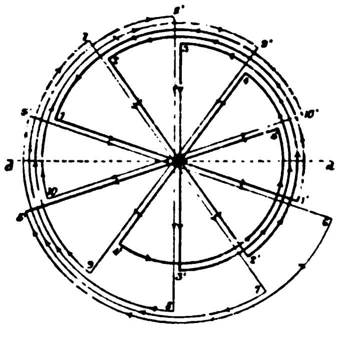


FIG. 264.—PACINOTTI'S DISK-ARMATURE.

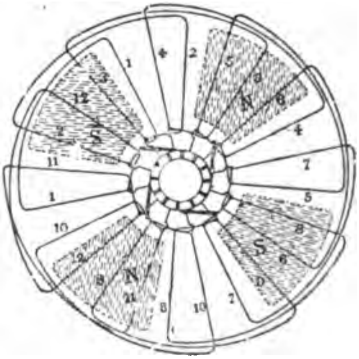


FIG. 265.—4-POLE DISK LAP-WINDING.

Disk Windings—These may be treated as drum windings extended radially, the outer periphery corresponding to the back end of the drum. The earliest such winding is that suggested in 1875, by Pacinotti. This is a lap-winding adapted for a 2-pole field, the N-pole being behind the upper part, the S-pole behind the lower part in Fig. 264. It will be noted that the outer end of each radial conductor is carried round by a peripheral connecting piece to join the end of another radial conductor, which for a 2-pole machine would be the one lying next but one to that which is diametrically opposite. The schematic figure relates to a 10-part armature, made up of twenty radial conductors. They are numbered so that the order of connexions may be traced. The diameter of commutation being *d d*, the currents flow radially inwards in one half and radially outwards in the other half of this disk. The construction of Pacinotti's experimental machines is described in his original paper.

---

[1] U.S.P. No. 646,092.

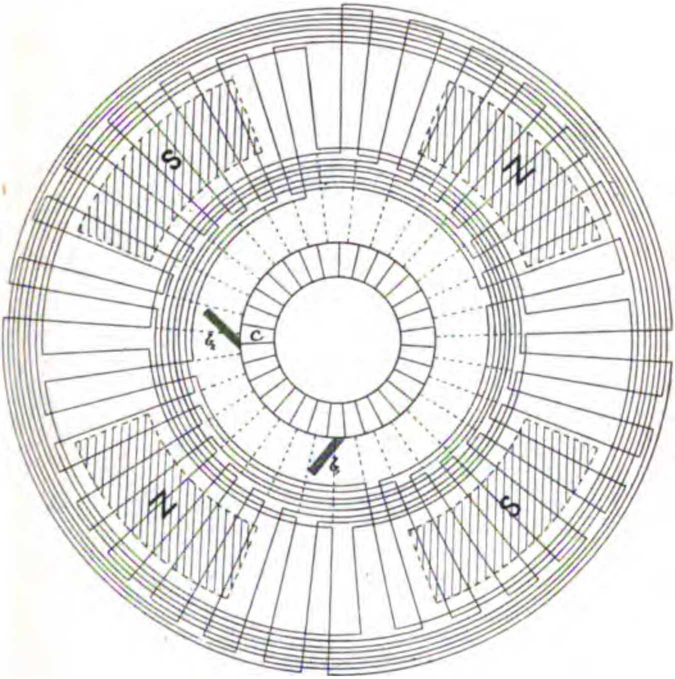


FIG. 266.—4-POLE WAVE-WINDING (MÜLLER).

Since then many suggestions have been made for windings of this description.

A lap-winding, identical with Pacinotti's but adapted to a 4-pole field, is depicted in Fig. 265; it is known as the Edison "new disk" winding. Bollman and Müller have devised multipolar disks with wave-winding.

Fig. 266 shows the connexions of a disk-armature designed by Müller[1] for a 4-pole machine in which the conductors passing in front of the different pairs of poles are placed in series. The brushes in this case are placed at 90° to each other.

Disk-armatures have been revived by Desroziers and Fritsche. Desroziers employs for a 6-pole machine the elaborate wave-winding shown in Fig. 267. A special study

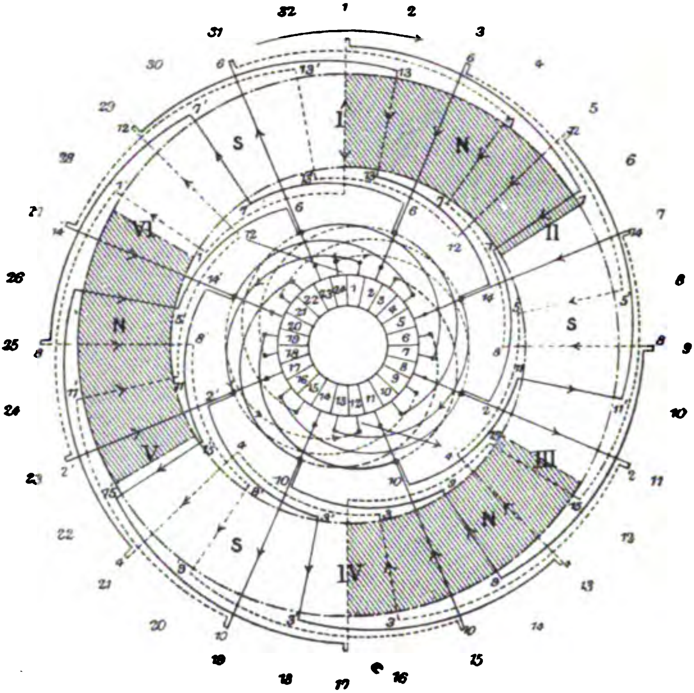


FIG. 267.—DESROZIERS' 6-POLE DISK-WINDING.

of this class of winding has been made by Arnoux.[2] Fritsche employs polygonal poles, enabling him to use, as conductors, strips of metal built up in star-polygon fashion without any radial parts—a structural advantage. His disk, if developed out straight would, for a 4-pole machine, be adequately represented by Fig. 246, p. 398. The two sets of conductors constitute two layers which are united at their outer ends to the bars of a commutator at the outer periphery.

---

[1] U.S. Patent, 331726 of 1885.

[2] See reference, p. 351.

The main difficulty in the employment of disk-armatures has been in the construction of an armature of this sort which is mechanically strong and capable of resisting wear and tear. Desroziers has done much to overcome this difficulty, and has produced machines which are very widely used in France and her colonies. He discerned that a disk-armature can be separated into two parts; that is to say, taking the alternate radiating conductors, the odd numbers for example, it is possible to build them and their connectors into a regular figure in one plane without troublesome over-crossings, and this plane of conductors can be superimposed upon a similar one built up of the other alternate conductors, so that the ends of the connectors coincide and only require to be soldered together to form a complete re-entrant winding.

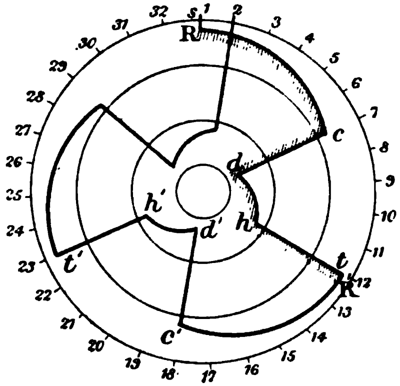
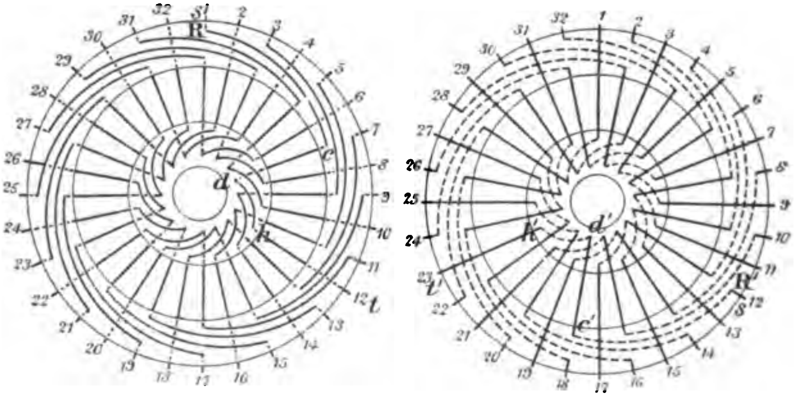


FIG. 268.—SKELETON DESROZIERS' WINDING.

This will be understood by reference to Figs. 268, 269 and 270. Fig. 268 shows six conductors joined in series forming part of a disk-armature intended for a 6-pole field, the current flowing inwards when passing one pole and outwards when passing the next pole of opposite sign. In order to mount a number of these conductors in series, they and their connectors may be taken in pairs and half of them mounted in the manner shown in Fig. 269, in which the portion R*cdht* will be recognised from Fig. 268. The other half are mounted as in Fig. 270, where the portion R′*c*′*d*′*h*′*t*′ is a continuation of the series in Fig. 268. In each of these planes of conductors the ends are brought out to the points numbered 1, 2, 3, &c., up to 32. By placing these two disks face to face, then soldering up the coinciding end and carrying those on the inside to the bars of a commutator we have a complete armature winding.



FIGS. 269 AND 270.—CONSTRUCTION OF DESROZIERS' DISK-ARMATURE.

It is obvious that there are other ways of dividing up the series of conductors shown Fig. 268 than the method adopted in Figs. 269 and 270. For instance, all parts similar to R*cd*, R′*c*′*d*′, &c., might be mounted to form one plane of conductors and the parts *dht*, *d*′*h*′*t*′, &c., would then form the other plane. In high voltage machines where a number of turns per segment are required, this can be done in the manner shown in Fig. 271, where the same letters are used to denote corresponding parts.

In practice there are two distinct methods of construction used: (1) wire-wound armatures; and (2) strip-built armatures. The wire in the former is threaded through holes in two concentric compressed cardboard rings that form the outer and inner supports for each plane of conductors. The two planes are then mounted face to face on a metal spider, the arms of

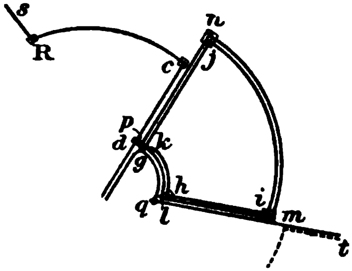


FIG. 271.

which, radiating from the shaft, pass between the two layers of conductors.[1]

Experience has failed to justify the existence of this type of machine : it has been superseded commercially by machines having the more mechanical armatures of drum or ring-pattern.

---

[1] For further particulars of these machines see *Electrical Engineer*, N.Y., xvi. 259.

CHAPTER XIV.

ARMATURE CONSTRUCTION.

ARMATURE construction is a branch of mechanical engineering. It involves, however, a certain knowledge of electrical principles and practice; a knowledge of conduction and insulation, and a multitude of miscellaneous items of information as to details which have been found useful in the development of the art. The present chapter deals chiefly with these details.

Core-Bodies.—Armature cores are always laminated, being constructed (1) of *disks* of sheet iron or softest mild steel; (2) of iron *ribbon*; or (3) of iron *wire.*

Wire cores were at one time largely in vogue, having been used by Gramme. The soft iron wire, varnished or slightly oxidised on its surface, was wound on a special former, then removed, taped externally, and wound with the copper wire conductors. Wire cores have three disadvantages: (i.) they are mechanically less satisfactory than disk cores; (ii.) they fill a given core-space with an actually less nett cross-section of iron owing to the interstices between the separate wires, only about three-fourths of the total cross-section being occupied by iron; and (iii.) they present a discontinuity radially which offers an unnecessary reluctance in the path of the magnetic lines. The substitution of a square iron wire for a round one, was an improvement in all these respects. But wire cores are now obsolete.

Machines for stamping and cutting core-disks and laminations for pole-tips, are described by E. Schulz in his *Technologie der Dynamo-maschinen* (1902), pp. 301–307, and by E. K. Scott in *Journ. Inst. Electrical Engineers*, xxxii. 368, 1903. Manufacturers who produce dynamo laminations, such as Messrs. Sankey, of Bilston, have innumerable patterns and furnish disks of all sizes with any prescribed numbers and forms of slots.

Core-Disks are stamped out of sheet, the usual thickness being 25 mils (= No. 24 B.W.G., or about No. 22 B. and S. gauge). A few makers use thinner core-disks, from 15 to 18 mils. It is usual to insulate the disks lightly from one another by covering one face with a single thickness of manila paper, or, in some cases, by painting one face with japan varnish, or with a water-glass enamel. The paper is pasted by machinery on the iron sheet prior to stamping. The mere existence of a film of oxide is sufficient insulation[1] in the case of very thin laminations. Core-disks not exceeding 30 inches in diameter are usually stamped out in one single piece. Those of larger diameter are generally built up out of segments. It is usual to stamp or cut the core-disks at first with a smooth periphery, and then to stamp out the slots in a subsequent operation. So accurately can the stamping be done that it is not necessary after assembling the core-disks, to mill out the slots, as used to be at one time done. The burr raised in milling is disadvantageous as it tends to defeat the proper insulation of the disks from one another. Nor can they be turned after being assembled. Should the outer periphery be found, after assembling, to be too irregular it may be ground, but should not be turned. Even lightly filing the slots may increase the iron losses in the armature by 15 to 20 per cent.

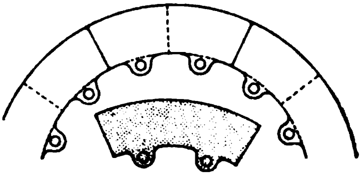


FIG. 275.—SEGMENTAL CORE-DISKS (KAPP).

Segmental Core-Disks.—The building up of core-disks in segmental portions is to reduce cost. The cores are constructed, as shown in Fig. 275, of pieces which overlap in successive layers, each piece having eye-holes for bolts, or else having dove-tail

---

[1] See paper by E. Schulz in *Electrotech. Zeitschrift*, 1893.

attachments. The bolt-holes must be at one-quarter and three-quarters of the length of the segment. Frequently the segments are stamped out of long sheets, to economise material, as shown in Fig. 276. Fig. 277 shows in Nos. 1, 2 and 4 the stages of manufacture of segmental pieces. It also illustrates in No. 3 one method of making a ventilating core-plate, with raised bosses and teeth turned edgeways.

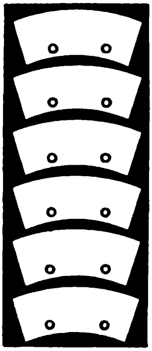


FIG. 276. STAMPING SEGMENTAL CORE-PLATES.

Forms of Teeth.—The most usual form of tooth is that shown in Fig. 278, slightly narrower at the root than at the top, the slots between having parallel sides. The corners are often slightly rounded. Occasionally, where several conductors are placed in one slot, the tops of the teeth are made projecting as in Fig. 279; this form having the advantage of presenting a larger magnetic area at the top, and of helping to hold in the conductors by the insulation of a wedge

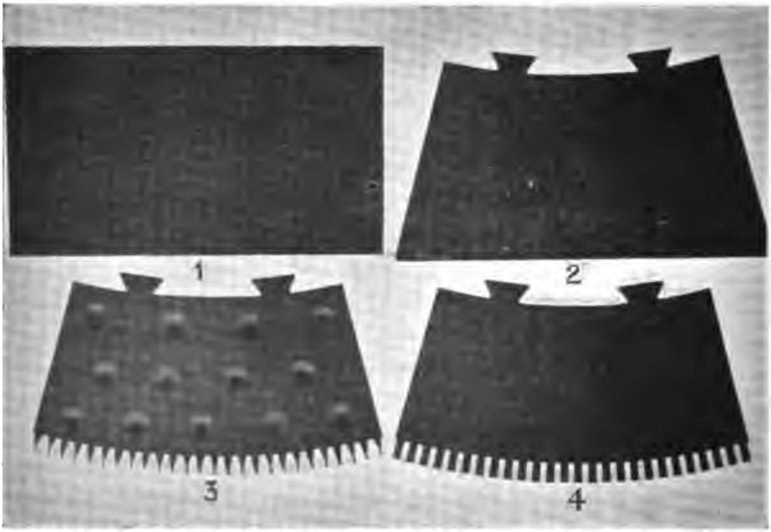


FIG. 277.—CORE-SEGMENTS AND VENTILATING SEGMENTS OF THE ENGLISH ELECTRIC MANUFACTURING CO.

of wood or hard fibre. The same end is attained by notching the teeth as in Fig. 283. Fig. 284 depicts a form with slots suitable for the reception of round wires.

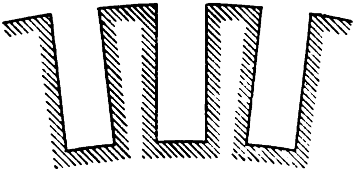


FIG. 278.—TEETH, WITH PARALLEL SLOTS.

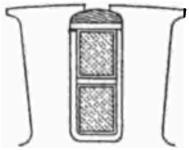
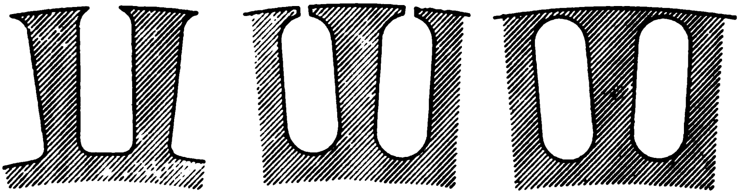


FIG. 279.—TEETH, WITH PROJECTING TOPS.

Figs. 280, 281 and 282 show forms of slot frequently used in alternators and alternate-current motors, though seldom employed for continuous-current machines. Armatures with closed slots like Fig. 282 are not used for continuous currents. Figs. 285 and 286 depict forms of teeth used in recent machines by Messrs. Ganz and Co. Fig. 287 depicts the core-disk of a small American motor having triangular teeth. This is constructed in two halves to facilitate winding.



FIGS. 280, 281, 282.—TOOTHED AND SLOTTED CORE-PLATES.

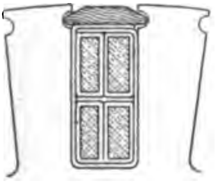


FIG. 283.—NOTCHED TEETH TO HOLD A WEDGE.

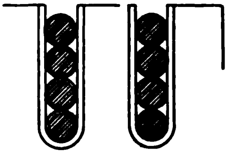
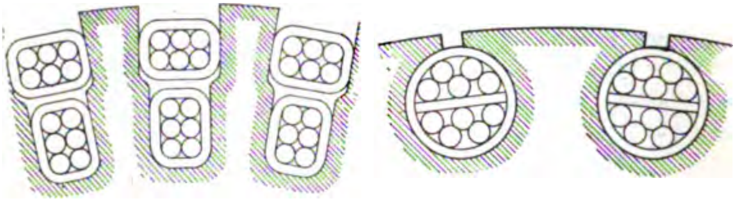


FIG. 284.—SLOTS ROUNDED AT BOTTOM.

For many years English makers, with some exceptions, preferred smooth core-disks to toothed forms. But with the advent of former-wound coils the use of toothed cores became universal. Fig. 288 depicts a group of armature cores and disks in the shops of the Westinghouse Company at Pittsburg. The cores with large T-shaped teeth are for alternators, whilst those with numerous narrow teeth are for continuous current armatures. Fig. 317, which gives a view in the winding shop of Messrs. Siemens and Halske, shows a group of core-disks all intended for continuous-current dynamos or motors.



FIGS. 285, 286.—FORMS OF TEETH USED BY GANZ AND CO.

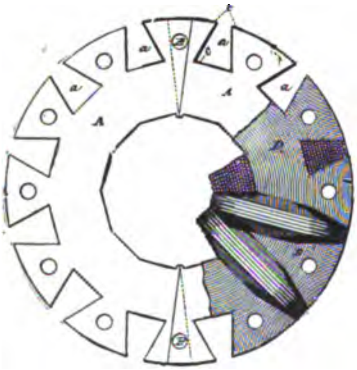


FIG. 287.—CORE OF ARMATURE OF MOTOR (CRUCKER-WHEELER).

End Core-Plates.—It is usual to insert at the ends of the core-plates cut from sheet-iron of a greater thickness so as to protect the thin laminations. A common thickness is 0·125 inch. Some makers also insert thicker plates at each face of any ventilating-duct.

Binding-wire Channels.—Some makers construct the core-body with shallow channels around the periphery at intervals to receive the binding-wires, that the latter may lie more nearly flush with the surface. To this end some of the core-disks will be stamped to a slightly reduced external diameter, the reduction being seldom more than 0·2 or 0·25 inch, giving

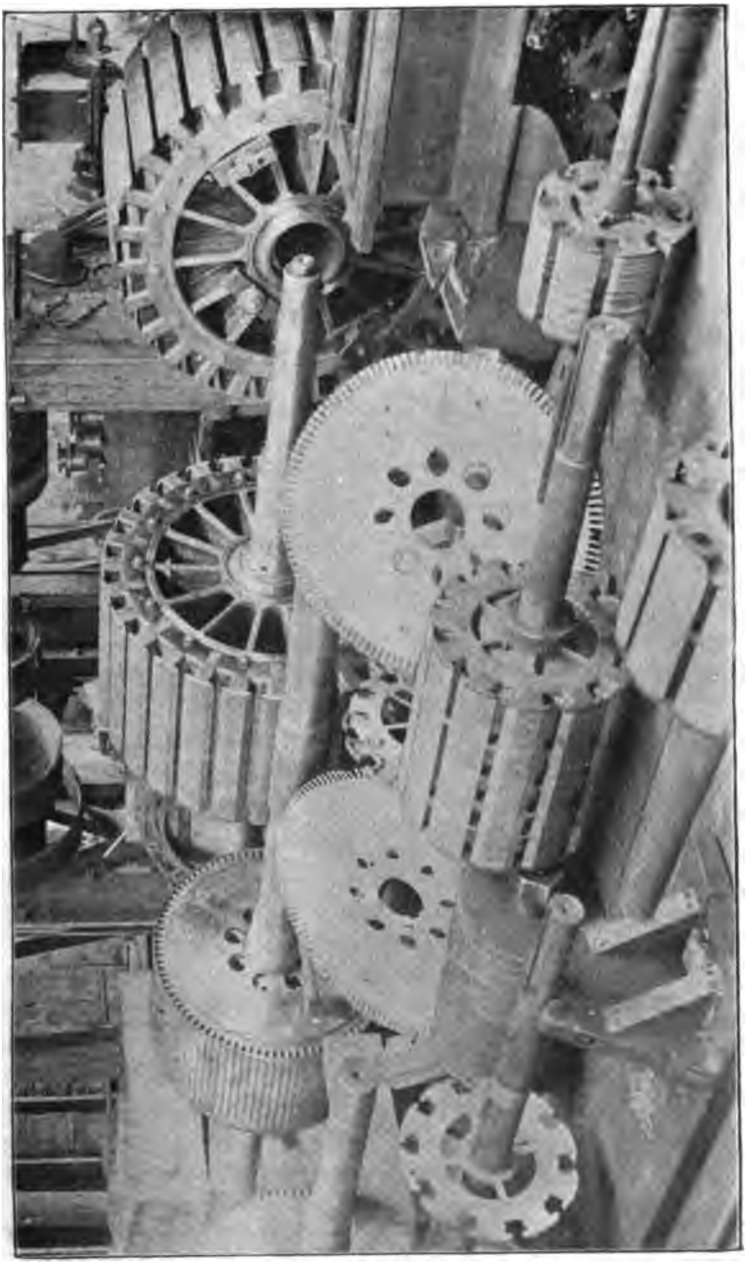


Fig. 288.—Group of Core-Disks (Westinghouse Electric Co.).

a channel $\frac{1}{16}$ to $\frac{1}{8}$-inch deep. As an example see Brown's armature Fig. 480.

Insulation of Core-Disks and Core-Bodies.—This matter is discussed in Chapter VIII. pp. 194, 195.

Mounting of Core-Disks.—Mechanical arrangements are required to hold the core-disks together, and to key them directly or indirectly to the driving shaft. In the case of small cores not exceeding 10 or 12 inches diameter they may be keyed straight upon the shaft. But in the case of large sizes, and especially for securing good ventilation, some frame or *spider* must be designed upon which they are held. Two cases present themselves according as whether the core-ring is stamped in a single piece or is built up of segments.

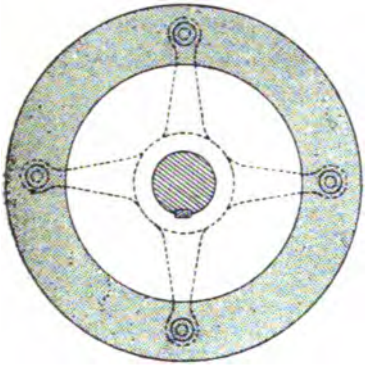


FIG. 289.—MODE OF DRIVING CORE-DISK.

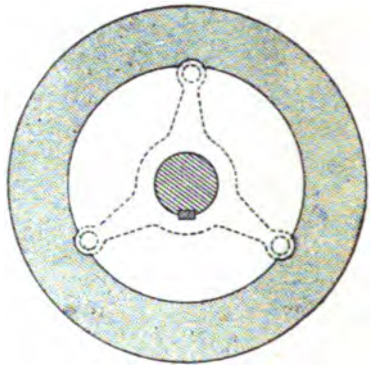


FIG. 290.—MODE OF DRIVING CORE-DISKS.

Fig. 289 shows the core-disks are held together by bolts passing through them, and driven by a skeleton pulley or spider keyed to the shaft. To this construction there is the objection that the bolt holes reduce the effective cross-section of iron and strangle the magnetic flux. It is also advisable that the bolts should be insulated[1] from the arms of the spiders by ebonite washers and bushes, otherwise the framework will constitute a closed circuit for eddy-currents which will heat it. Arnold has given rules for calculating this loss, but in most cases it is very small. A better mode is that of Fig. 290, in which the section of the iron is but slightly reduced and the bolts are entirely internal to the core. In this case the bolts need not be insulated at all, as in revolving they do not cut any appreciable number of magnetic lines.

---

[1] See, however, remarks by Fischer-Hinnen in *Schweiz. Blätter für Electrotechnik*, Feb. 1898; or *Continuous-Current Dynamos*, p. 289, London, 1899.

Another mode, introduced by Crompton in 1886, is to provide the core-disks with dove-tail notches into which pass long flanges from the shaft. In another form, a ribbed sleeve, which slips over the cylindrical shaft, is driven by a long feather.

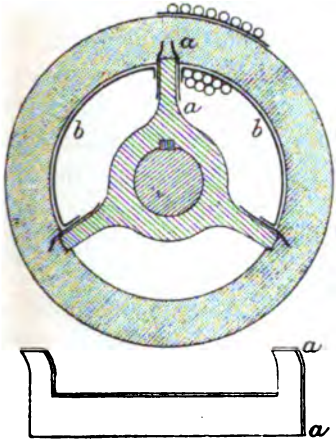


FIG. 291.—KAPP'S METHOD OF DRIVING CORE-DISKS.

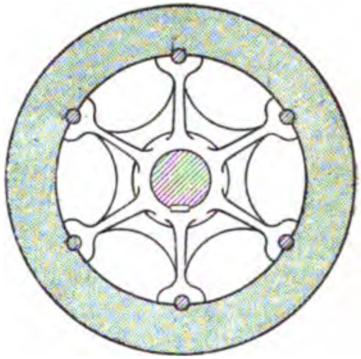


FIG. 292.—DRIVING CORE-DISKS BY KEY-BOLTS (BROWN).

Kapp's mode of driving the core-disks for a ring-armature is shown in Fig. 291, which should be compared with Plates II. and III. Over the sleeve is slipped a long sleeve provided with three projecting flanges to support the core-disks. This sleeve, keyed by a long feather slightly sunk into a keyway on the shaft, helps to stiffen the shaft. In armatures for ring-winding, such internal structures should be of brass or gun-metal: in those for drum-winding, they may be of cast-iron. The armature sleeve or hub is, in this example, pushed up toward a face-plate, which rests against a shoulder on the shaft; and the core-disks are tightened together between the two face-plates by a nut on the shaft. Figs. 292 and 294 show modes of supporting due to Brown: Fig. 294 should be compared with Plate IX. It is moreover necessary to compress the core-disks tightly together, and means for this must be provided. Bolts passing through stout end-plates suffice in small machines. In larger machines it is usual to employ end clamping-rings, the outer periphery of which does not extend beyond the roots of the teeth. Some makers cut out the periphery till it forms a series of claws. The object of this is to keep the mass of it as far away as possible from the magnetic field. For an example see Plate XVII.

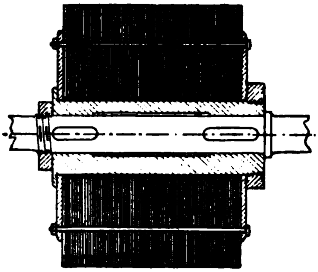


FIG. 293.—CORE-DISKS CLAMPED ON A SLEEVE.

In Fig. 294 there are employed two spiders each having 4 internal web-spokes and wide end-flanges. Each has a longitudinal feather to prevent it from turning upon the shaft. One of them is held up against a shoulder on the shaft, the other one is pressed up by a large hexagonal nut. Two of the webs on each spider are ribbed; the core-disks being stamped with notches to prevent them from turning. Of the four web-spokes two are long and two short, so that the core-disks may be compressed as the spiders are forced together. Many makers now use similar arrangements.

In Fig. 292, which is more recent, round steel keys are driven into grooves cut in the ends of the spider flanges, and in the core-rings.

The use of stout end-plates drawn together with screw-bolts to compress the core-disks is also illustrated in the Plates V., IX., XVI. and XIX.

Fig. 295 shows a recent design by the Oerlikon Co. in which the core-rings are assembled on a light pulley-like structure of cast-iron. At the left-hand end a stout face-plate, with a bracketed extension for supporting the projecting conductors, is tightened up by screws. The right-hand end of the hub is extended upward into a coned flange which presses against the core-rings, and at the same time serves as a bed to support the recurving armature windings. A cast-iron shield to protect these windings is secured by independent bolts and nuts.

Other kindred modes of constructing the mounting will be found in various drawings. The reader is referred particularly to the details of Figs. 425, 442 and 445, and of the Plates.

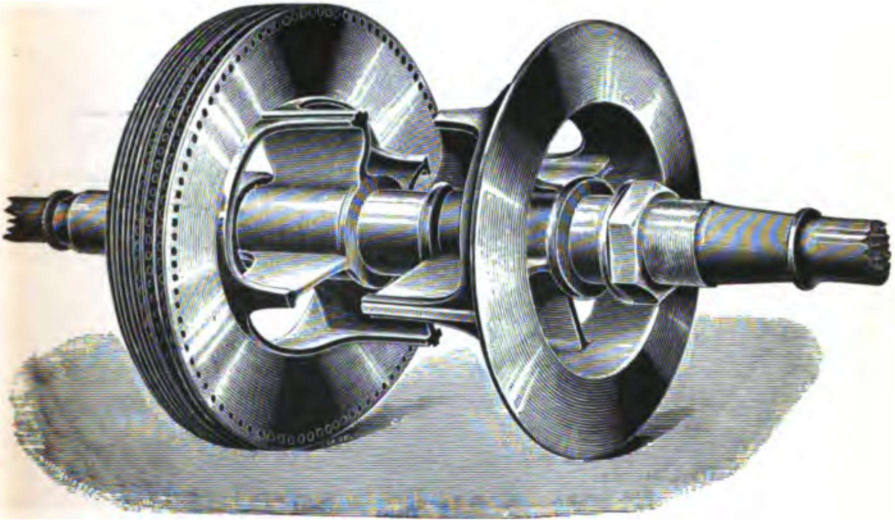


FIG. 294.—BROWN'S MODE OF DRIVING THE CORE-DISKS.

The hubs of armature spiders are, for securing better fit to the shaft, usually cleared out between their front and back bearing surfaces, and in the larger sizes, at least, it is not uncommon to find the seating on the shaft turned to two different sizes to admit of easier erecting, as in Fig. 296.

For supporting segmentally built cores more elaborate arrangements are needed. The armature spider is constructed with a substantial hub from which radiate a number of arms, and these carry a species of rim furnished either with

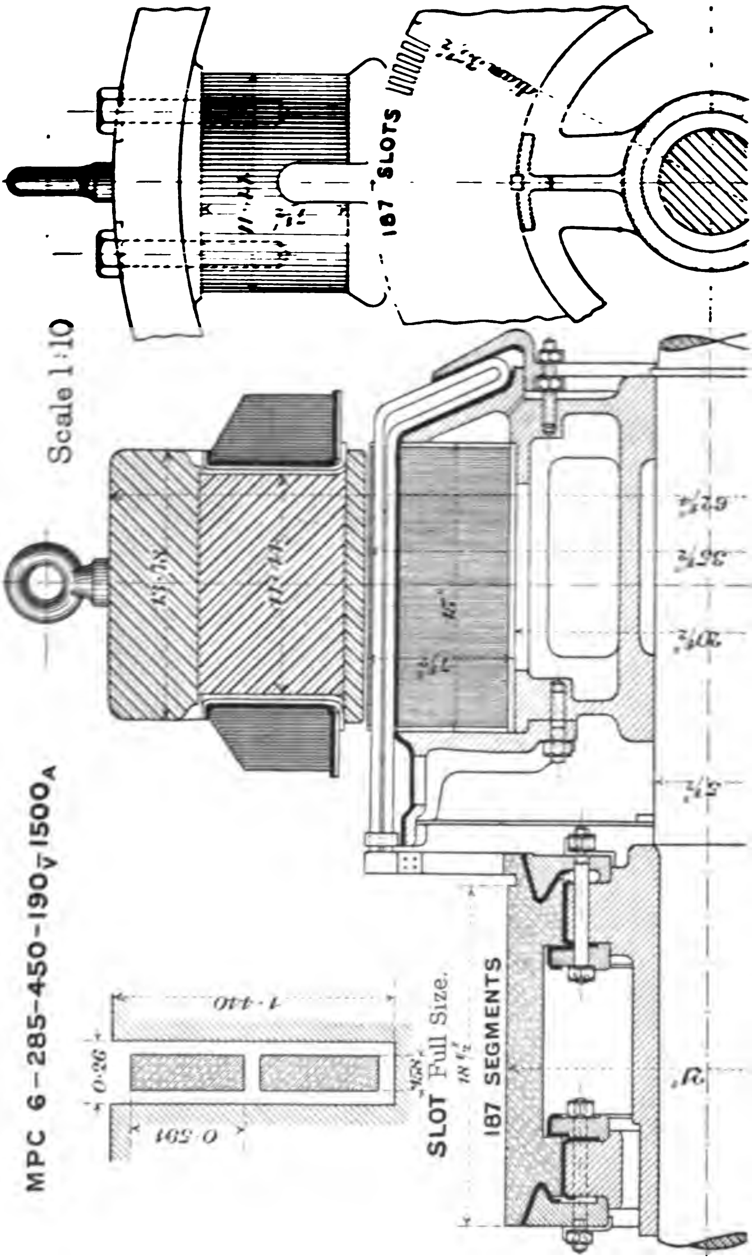


FIG. 295.—OERLIKON CO.'S 6-POLE ELECTROLYTIC GENERATOR AT ROME.

dovetail projections to fit into notches in the assembled core-disks, or else with dovetail grooves into which fit corresponding projections of the core-disks. In the latter case the bolts which hold together the core-disks may be carried through these projections as shown in Fig. 297.

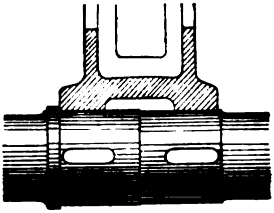


FIG. 296.—CONSTRUCTION OF ARMATURE HUB.

Such a spider also often serves to carry the bracketed rims which support the projecting end-parts of the windings. They have the advantage of providing ample ventilation for the core-disks.

Fig. 298 shows the spider of the 1100 kilowatt generator of the English Electric Manufacturing Company, which is described on p. 691. The rim is here cut into 6 pieces each of which has 4 dove-tail notches. If the rim were cast in one continuous piece trouble might arise from unequal contraction of the casting. Ventilating apertures are provided, and on the side of each arm are seen the seatings and bolt-holes for

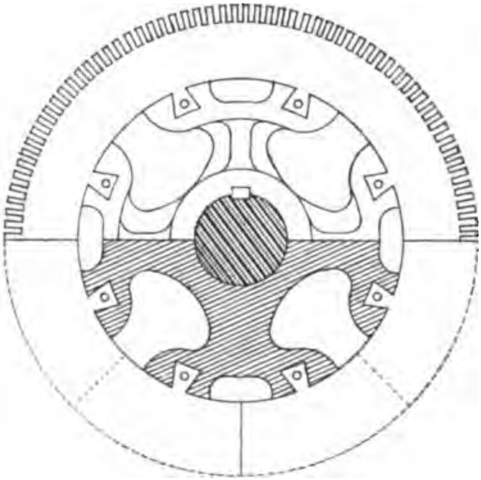


FIG. 297.—ARMATURE SPIDER.

attaching the commutator-hub and the rim which supports the windings.

Fig. 299 shows the next stage of construction, namely, the assembling of the core segments. In this figure and in Fig. 300, which depicts the completed core, are visible the supporting rim and narrow ventilating ducts.

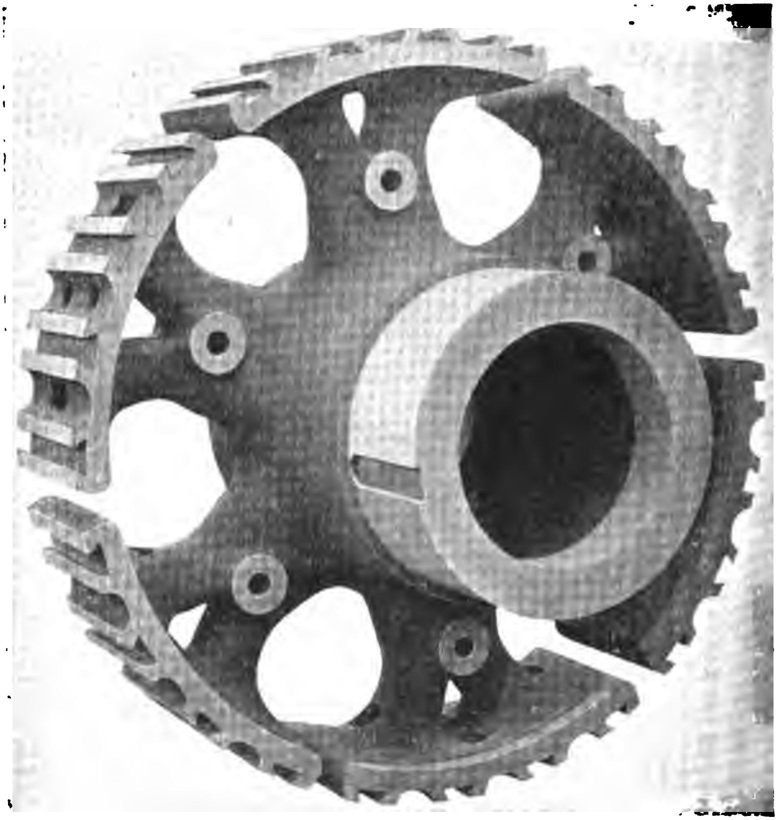


FIG. 298.—SPIDER OF THE ENGLISH ELECTRIC MANUFACTURING CO.

Ventilating Ducts. — Armature cores heat from three causes: hysteresis; eddy currents; and heat derived from the copper conductors. The careful lamination and insulation

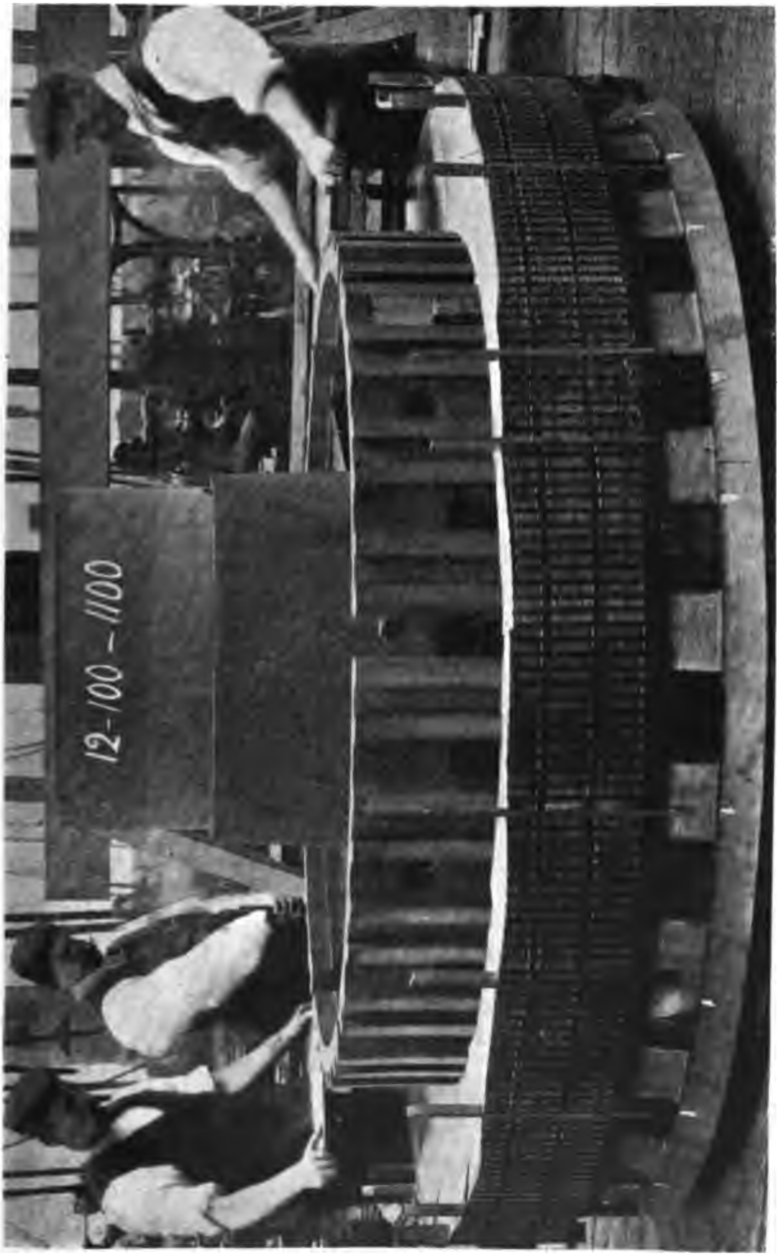


Fig. 299.—Armature Core Building; English Electric Manufacturing Co's. Continuous-Current Generator, 12-poles, 1100 kw.

described above are but means to prevent waste of power and to avoid risk of overheating. In the case of ring-wound machines there is usually an amount of surface exposed

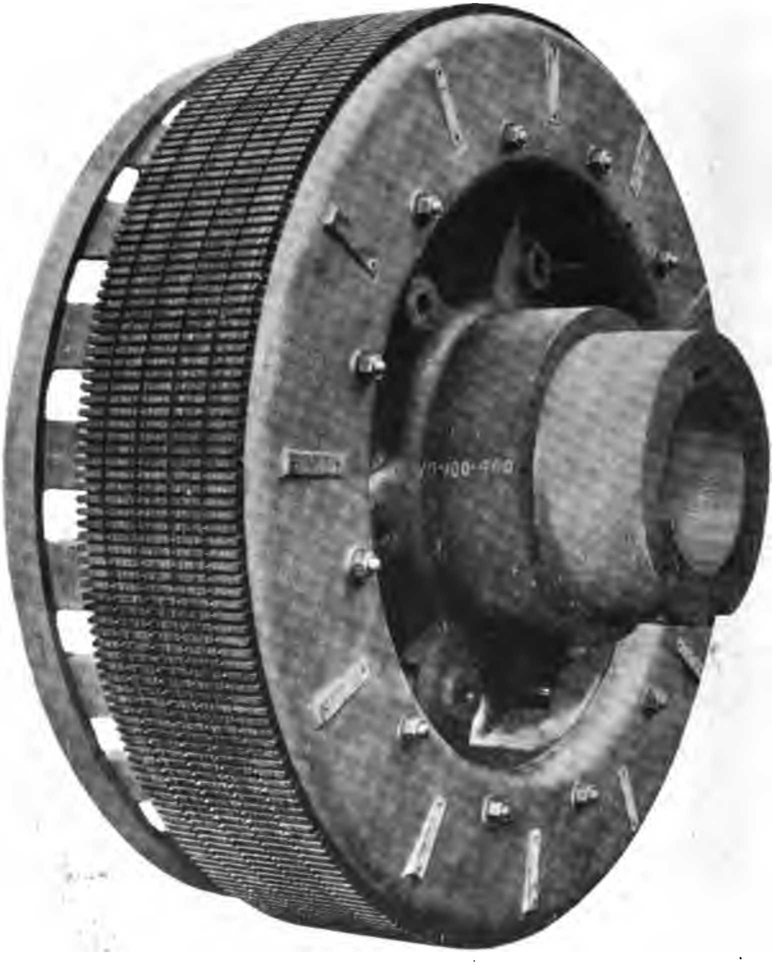


FIG. 300.—COMPLETED CORE.

sufficient to get rid of the heat generated in the conductors without resorting to any special mode of ventilating. But in the case of large and solidly constructed drum-armatures some mode of forcing the ventilation may be necessary. For twenty years it has been customary to make longitudinal apertures through core-bodies: but the practice of providing special ducts that lead the air between the core-disks and open into the gap under the pole-pieces is more recent. Small ducts are seen in the Kapp armature, Plate III., constructed in 1887, one of the earliest examples. In drum-armatures with the old-fashioned wire-winding overlapping the ends, adequate ventilation is impossible. As examples of ventilated

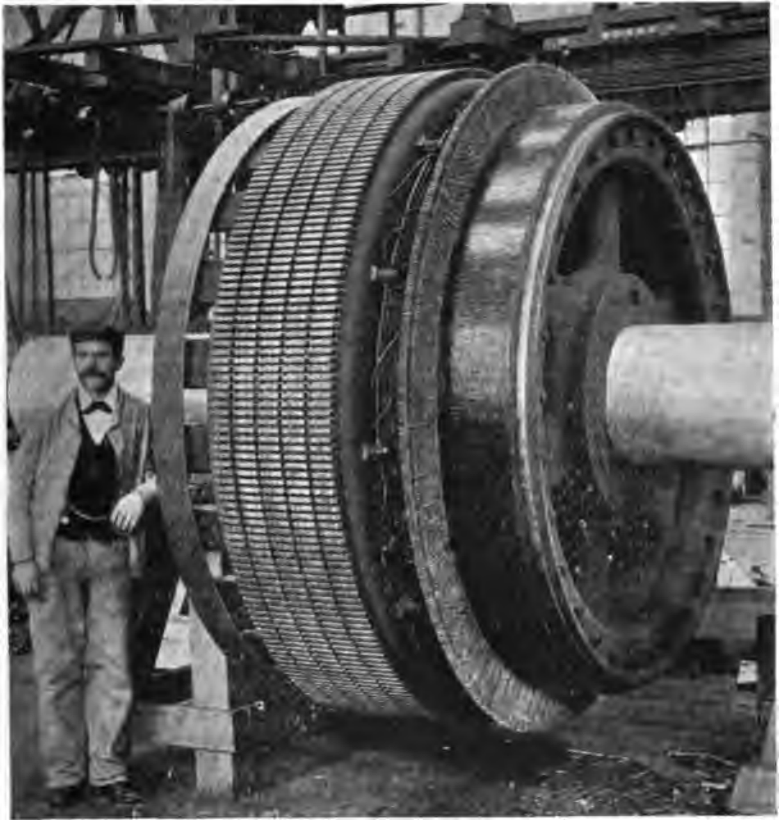


FIG. 301. — ARMATURE CORE WITH COMMUTATOR IN PLACE, AND EQUALISING CONNECTORS, READY TO RECEIVE THE WINDINGS.

cores the reader should see Brown's drum-armature, Plate IX., and several of the other Plates.

To keep the core-disks apart at these ducts it is necessary to introduce distance pieces or "ventilators." Fig. 302 *a*, *b*, *c*, illustrate some of these devices. Simple pieces of brass are riveted radially at intervals to a special core-disk about 0·040 or 0·060 inch thick.

This simple form fails to give support to the teeth, a defect which is obviated in Fig. 302 *c*, where behind each tooth there is a strip of brass about 0·4 or 0·5 inch wide set edgewise, being cast with or brazed to a special casting of brass that is riveted to a stout core-disk. This form is used by the British Thomson-Houston Co. A simpler device, shown in Fig. 277 (3), p. 424, is that of bossing up a number of projections in a core-disk, and of bending the teeth round through a right-angle. Modern barrel-windings have, from the ventilation point of view, an advantage over the older type of drum-winding

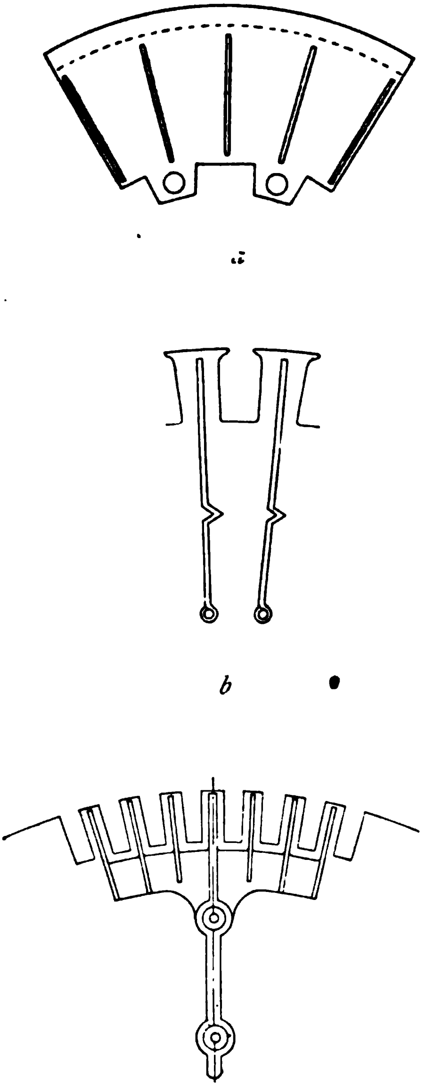


FIG. 302.—VENTILATING DEVICES.

with end spirals. In the latter the arrangements with one set of evolute spirals and one set of straight radial pieces (as in Fig. 235, p. 390) are sometimes preferred to those with two sets of spirals as in Fig. 236, p. 391, as having a better fan action. Some makers use spiders with arms sloped like the sails of a windmill, so as to propel air through the interior of the armature.

Driving Horns.—In the days when smooth-core armatures were in vogue it was requisite to provide driving horns to propel the conductors. An example is seen in Plate II. But with the adoption of toothed cores this device has become obsolete, save in exceptional cases. Machines for furnishing a large output of current at a low voltage for electrolytic purposes are occasionally so constructed to reduce the self-induction of the armature windings. In such a machine built at the Oerlikon works, the core-disks were simply notched with a semicircular notch in which the insulated conductors were laid. At the ends a strong German-silver core-disk pierced with holes, held the conductors from flying out.

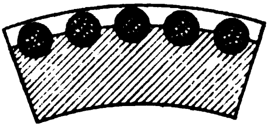


FIG. 303.—MODE OF DRIVING ROUND CONDUCTORS.

Binding Wires.—In the case of smooth cores the conductors must be secured in their places by a number of external bands, known as *binding wires.* In the case of toothed core-disks the conductors may be held in by *wedges* driven in under the tops of the teeth; or in the case of straight teeth binding wires may be used instead of wedges. Binding wires must be strong enough to resist the centrifugal forces, and yet at the same time must occupy very little radial depth that they may not interfere with the clearance between the armature and the pole-faces. The almost invariable practice is to employ a tinned wire, of hard-drawn brass, phosphor-bronze, or steel, which, after winding, can be sweated together with solder into a continuous band. Mr. Wall, of Sheffield, manufactures a special "plated steel" wire for binding, in sizes of 18, 22, 28, 36, 48 and 56 mils diameter respectively. Phosphor-bronze will withstand a tensile stress of from 65,000 to 120,000 lb. per square inch. Steel varies from 125,000 to 230,000 lb. per square inch.

Some makers bind the conductors over their projecting end-portions only with broad bands of delta-metal, or with belts of wires sweated together throughout their whole length, but secure the wires in the slots either by wedges, or by narrow belts of wires, soldered only to secure their ends.

To estimate the proper size and number of binding wires required we may remember that on a pound of material at a given radius, revolving at a given speed, the centrifugal force will be that given by the formula on p. 468. Or if d be the diameter in inches, and n the revolutions per second, the centrifugal force per pound of matter will be $= 0{\cdot}012\, d n^2$ pounds' weight.

Suppose we know the mass w_1 (in pounds) of one conductor, multiplying this by the total number of conductors Z, we get the total mass of armature conductors, and dividing by π we find the mass that will be effectively projected in any one direction. Putting this into the formula, and dividing by 2, we find the total tensile force to be borne by the binding wires at one side; and dividing again by the maximum tensile stress which the material can stand, we obtain the net theoretical total cross section of the whole of the binding wires. Taking a factor of safety of 10, and a value of 100,000 lb. per square inch as the tensile stress for steel or for phosphor-bronze, we get total necessary section of binding wires in square inches

$$= \frac{w_1 \times Z \times 0{\cdot}102 \times d'' \times n^2 \times 10}{2 \times \pi \times 100{,}000};$$

$$= \frac{1{\cdot}623 \times w_1 \times Z \times d'' \times n^2}{1{,}000{,}000}.$$

From this total necessary section, and the appropriate wire-gauge, the number of wires is then calculated, and they are then arranged in suitable belts.

Example.—$w_1 = 0{\cdot}39$ lb.; $Z = 1536$; $d = 62''$; $n = 2{\cdot}5$ revs. per sec.; total necessary section works out to 0·386 square inch.

Referring to wire-gauge tables we find a No. 17 S.W.G. of diameter 56 mils, has a cross-section of 0·00246 square inch. Dividing 0·386 by 0·00246 we find that 156 wires are needed. These may be arranged as follows, 5 belts of 16 wires each over the core-body, and 4 belts of 19 wires each over the extended ends of the winding, *i.e.* 2 belts of 19 wires each over each end.

Under each belt of binding wires a band of insulation is laid. This usually consists of two layers, first a thin strip of thin vulcanized fibre or of hard red varnished paper, slightly wider than the belt of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each belt of binding wires, having tags which can be turned over, and soldered down, to secure the two ends of the binding wire from flying out.

Below are given particulars of the bindings adopted for smooth-core armatures of the Edison bipolar dynamos.

Output of dynamo in kilowatts . .	1	10	30	50	150
Revolutions per minute . . .	2100	1600	1200	700	450
Length of armature body (inches) . .	$6\frac{1}{2}$	12	18	$24\frac{1}{2}$	$26\frac{1}{2}$
Diameter of armature body . . .	$3\frac{1}{2}$	$6\frac{1}{4}$	$9\frac{3}{16}$	$12\frac{15}{16}$	$23\frac{3}{4}$
No. of binding bands on body . .	6	7	9	13	7
No. of strands in each band . . .	22	19	21	18	24
Gauge of brass binding-wire (B.W.G.) .	25	23	21	19	19
Width of mica underlay 0·01 inch thick .	$\frac{5}{8}$	1	1	$1\frac{1}{8}$	$1\frac{1}{2}$
Number of clamps (of copper sheet, 14 mils thick and $\frac{1}{8}$ to $\frac{1}{4}$-inch wide) on each band	2	3	4	4	6

Wedges.—In the cases where wedges are driven in between the teeth to hold the conductors from flying out, the usual material is well-baked hard wood, such as hornbeam, or hard white "vulcanized fibre." A modern method is to use a springy strip of German silver, or of the new alloy "magnalium."

Conductors.—Copper conductors may be considered under the headings of *round*, *rectangular*, and *stranded.* Round wires are usual in small armatures and in armatures of very high voltage. But with them the space-factor is always low, and wires of rectangular section are *always* preferable. Rectangular conductors made of drawn copper strip are now furnished by the wire-drawers in many different sizes and sections ; the disadvantage of them is their lack of flexibility. Laminated conductors, made of a number of thin strips laid upon one another to the requisite total section and taped together, have an advantage in this respect. Stranded conductors are seldom used except for smooth-core armatures, the object of stranding being to eliminate eddy-currents in the copper. See p. 160.

Armature Windings.—Given a scheme of winding according to any of the modes discussed in the preceding chapter, the problem remains how to carry it out in the factory.

A broad distinction may be set up between *wire-wound* armatures and *bar-wound* armatures, the latter term denoting a construction built up of copper bars or of specially shaped rods that are joined together instead of being wound on. Wire-wound armatures are subdivided into the classes of *hand-wound* and *former-wound.* As a rule bar-windings are more mechanical than others. It is partly for this reason that series-groupings and series-parallel groupings (p. 369) are often preferred in multipolar machines. Single round wire insulated with double cotton covering, wound on dry, and afterwards soaked with "Sterling varnish," is usually adopted for hand winding in small machines and for arc-lighting machines. Silk-covered wire is practically never used. In small electroplating dynamos it is frequent to find a hand-winding of several small wires in parallel, even to as many as twenty or thirty separate wires side by side serving as a single conductor.

Bar-Windings.—For bar-armatures, rectangular bars set *edgewise* in slots are almost universal. Round bars are very rarely found in continuous-current machines. Smooth-core armatures do not lend themselves to bar-winding, because solid copper bars set on the outside of a smooth core are liable to a serious waste of energy that does not occur in small-wire windings. When the conductors present any considerable breadth, there is a tendency to set up eddy-currents in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the density of which is very different from that of the field through which the other edge is passing. For example, if the surface speed is 3000 feet per minute, and the bars are ½ inch wide, it may be that the front edge may be in a field of density, say, of 40,000 lines per square inch, while the other edge is one of 30,000 only. If the active length of the conductor is, say, 12 inches, then its front edge will be cutting magnetic lines at the rate of 288,000,000 lines per second, and therefore the induction in that edge will be 2·88 volts; while in the hind edge the corresponding induction will be only 2·16 volts. The difference, or 0·72 volts, will tend to set up an eddy current flowing up one edge and down the other edge of the bar. Suppose the bar to be ⅛ inch thick: if for the purpose of argument it is regarded as equivalent to two parallel bars ⅛ thick and ¼ wide united at the ends, the resistance round this elongated loop will be that of a rod of copper 24 inches long and of 0·25 × 0·125 square inches of cross-section. At 60° C. this resistance will be only 0·000607 ohm; and an electromotive-force of 0·72 volts would set up a current of 1186 amperes! But as the electromotive-force is 0·72 between the extreme edges only and has lesser values towards the middle of the width, the eddy-current up and down the strip will be less than this. Even if one takes a twentieth part of the value so found as being more probable it is serious enough from the heating and waste of power that it entails: for at no-load there would be this waste in each conductor as it approached and left each pole. At full-load there might be no actual eddy-current. For if the full-load current through the conductor were 150 amperes, then superposing upon this an eddy-current of 59 amperes in the two halves of the conductor (as in Fig. 305),

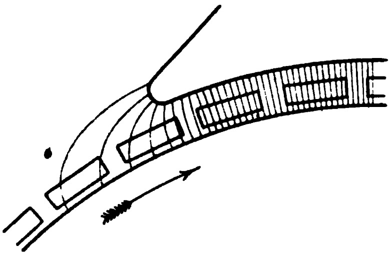


FIG. 304.—UNEQUAL INDUCTION IN EDGES OF FLAT BAR.

the result would be that in one half of it the current would be $75 + 59 = 134$ amperes, and in the other half $75 - 59 = 16$ amperes. The 150 amperes no longer distribute themselves equally through the breadth of the strip; and the total heating of the strip would be precisely the same as if the eddy-current were really there. At the peripheral speeds actually used, it is found impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on a smooth core if their width exceeds 0·2 inch.

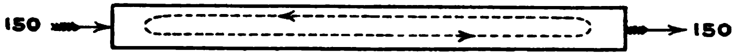


FIG. 305.—EDDY-CURRENT IN WIDE BAR.

In sunk windings these losses practically do not occur, unless the slots are very narrow and deep so that there is a magnetic leakage across the slot from tooth to tooth. In the case of a conductor being made up of several wires in parallel, the separate wires must not lie in different slots, for reasons similar to those already discussed.

To eliminate such eddy-current losses Crompton[1] proposed several methods of twisting or imbricating around one another two or more strips, so as more effectually to neutralise the eddy-currents. He introduced the use of bars made of stranded wire compressed into a rectangular form, each wire being oxidized or lightly insulated.

DRUM-WINDINGS.

There are several varieties of drum-winding, viz. (1) hand-winding; (2) evolute-winding; (3) barrel-winding; (4) bastard drum-winding; (5) former-winding.

Drum-winding was invented in 1872 by Von Hefner Alteneck, of the firm of Siemens and Halske. The process of constructing the armature down to the year 1885, is illustrated in Fig. 306; there being two layers of coils, hand-wound, all over the cylindrical core. Although for the sake of rendering the connexions more intelligible, the commutator is shown in Fig. 306 in its place on the shaft, it is not, as a matter of fact put into its place until after all the sections have been wound, the ends of the wires being temporarily twisted together until all can be soldered to the risers. The cores of these early machines were of wood overspun circumferentially with iron wire before receiving the longitudinal copper windings.

---

[1] See *Journ. Instit. Electr. Engineers*, xix. 240, 1890.

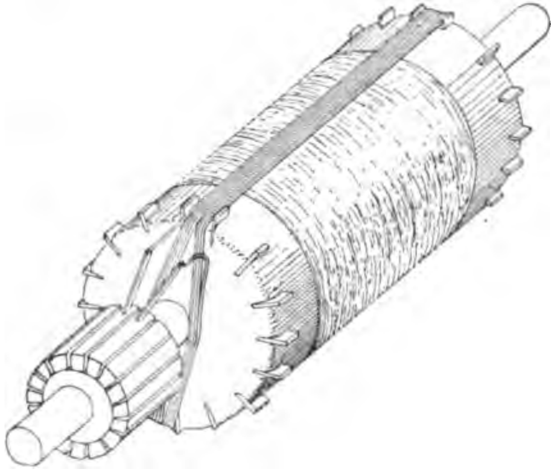


FIG. 306.—METHOD OF WINDING SIEMENS' ARMATURE.

So far all is simple: but when one passes to the construction of bar-armatures, complications arise. To connect the bars across the ends of a drum is not so simple a matter as might at first appear. Suppose that a scheme of connexions has all been worked out beforehand, and that a winding-table has been prepared in which the order of the end-connexions is set down. It yet remains to determine the mechanical devices for the end-connectors which shall be compatible with working conditions. The end-connectors must be good conductors, sufficiently well insulated from one another, allowing of repairs and ventilation, and mechanically sound. Hand-wound drums present an ugly overlapping at the ends, which stops ventilation and hinders repairs; and the outer layers overlie those that have been first wound on, producing dissymmetry, and bring into near neighbourhood conductors at very different potentials.

Evolute Winding.—Quite early, Messrs. Siemens devised, for their electroplating machines, a system of uniting by spiral connectors (Fig. 307) the ends of the copper bars. To connect any bar with that lying next to the one diametrically opposite, two evolute spiral strips of copper were applied, one bending inwardly the other outwardly, their junction being mechanically secured to a block of wood on the shaft. Their outer ends were attached to the bars by silver solder. At each end of the drum these spiral connectors constituted two separate layers. Thus began the system of *evolute-winding* which, with more or less modification, was the accepted form of drum armature down to about 1894, and is still largely used. A common form of conductor cut from sheet copper is illustrated in Fig. 308; a second form is made of strip folded. It is usual in large machines to anchor the middle part of each evolute to a hub of wood, or to an

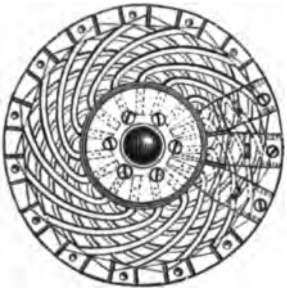


FIG. 307.—SIEMENS' BAR ARMATURE.

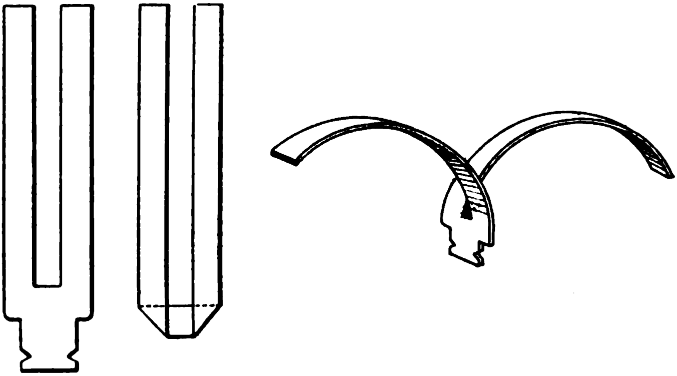


FIG. 308.—EVOLUTE CONNECTORS.

(insulated) clamping device, built up like a commutator, and sometimes called a "false commutator." See for example the Oerlikon machine, Fig. 450, and the Kolben armature, Plate XVII.

Edison's modification of the drum-armature was constructed of solid bars of copper; their ends being connected across by washers or disks of copper, insulated from each other, and having projecting lugs, to which the copper bars were attached. The construction was mechanically excellent, but it did not admit of ventilation; and the stray field at the ends of the armature set up eddy-currents in the substance of the copper disks. It was therefore abandoned.

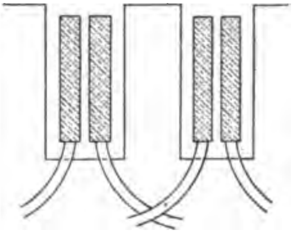


FIG. 309.

In evolute-winding, as the spiral connectors lie in two planes one behind the other at the ends of the drum, it is necessary that the conductors which lie in the slots should project to different distances beyond the core-body, the

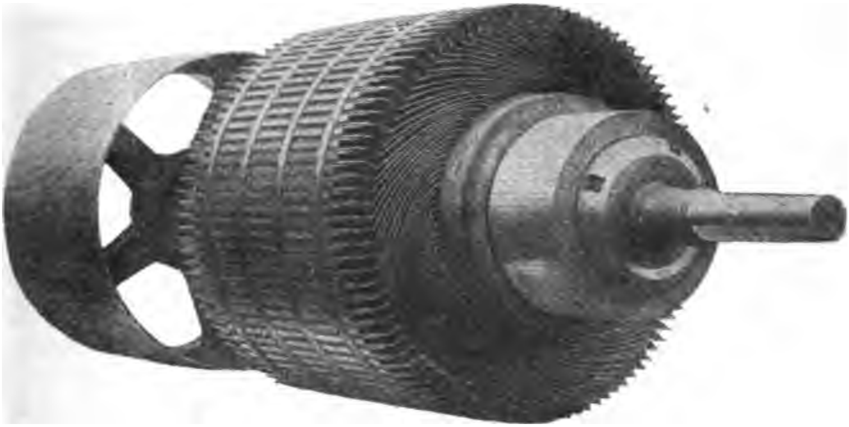


FIG. 310.—4-POLE, 60 KILOWATT, DRUM ARMATURE OF THE OERLIKON CO.

shorter ones being joined to the inner range of evolutes, the longer ones to the outer range. For this purpose it is convenient to arrange the conductors two in a slot, and these are usually side by side as in Fig. 309; one short and one long conductor being set side by side. This is also seen in the finished armature, Fig. 310, of the Oerlikon Company. It can be used for either lap-windings or wave-windings.

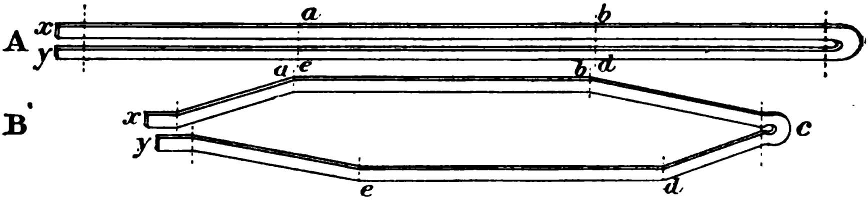


FIG. 311.—ELEMENT OF LAP-WINDING FORMED FROM STRIP.

Barrel-Winding.—About 1892 Mr. C. E. L. Brown devised the plan of arranging the conductors in two layers, so that their ends instead of being turned down in evolutes, are carried out in the cylindrical surface and bent to meet obliquely in two overlapping layers. This plan, known as *barrel-winding*, or in German as *Mantel-wickelung*, has been very widely adopted. It has the disadvantage of making the gross length of the armature somewhat greater; but on the other hand it lends itself admirably to ventilation, and furnishes a larger cooling surface. It is usual to furnish the armature body with ventilated projecting brackets at the ends to support the windings. A very simple method of constructing such windings is to take a long strip of copper of the desired section, and to bend it into the form shown in Fig. 311 A, which is then opened out and bent to form a single turn of a lap-winding, the portion *a b* destined to be an upper conductor, the portion *d e* a lower conductor; the

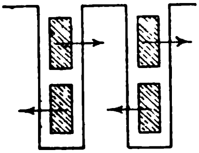
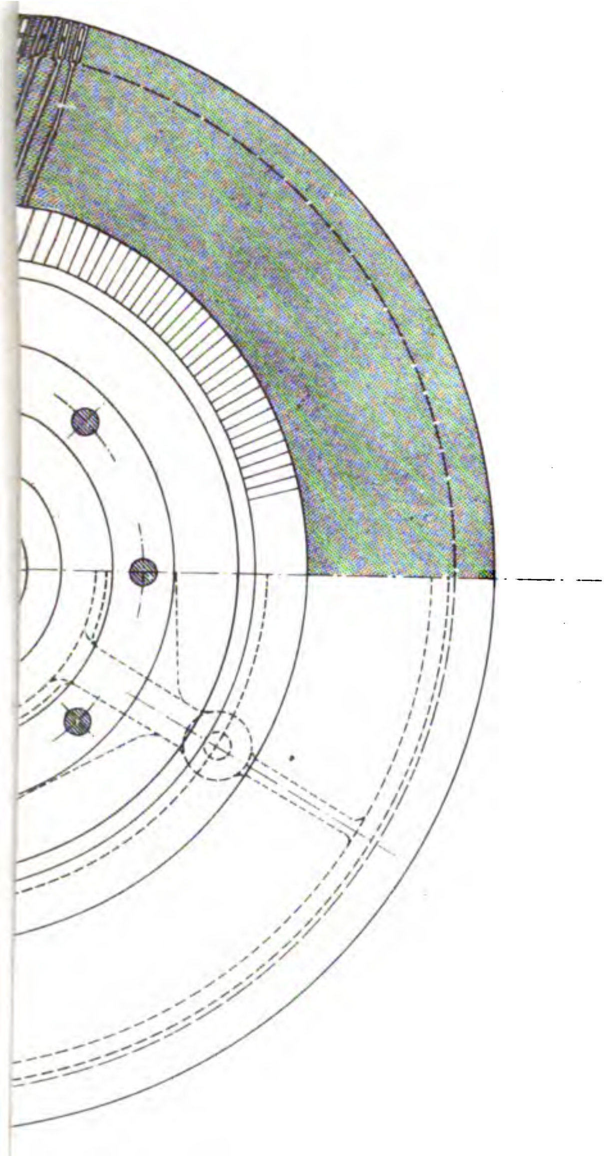


FIG. 312.

Scale 1:6



conductors being arranged two in a slot, one above the other, as shown in Fig. 312. For lap-winding the ends *xy* are bent towards one another to be joined to the ends of the next laps respectively, as shown in Fig. 313. To adapt the plan to a wave-winding the ends will be bent outwards (as in Fig. 219, p. 364), and as in Fig. 314, which shows the upper and under conductors formed of two separate parts. Plate IX. gives a scale-drawing of a large drum by Brown, with such a winding, and Fig. 316 gives a view of the complete armature. It shows also how the binding wires are disposed over the core-body and over the projecting ends of the winding. It is easy to tell at a glance whether a barrel-wound armature is lap-wound or drum-wound, since the upper layer of oblique ends bends differently in the two cases,

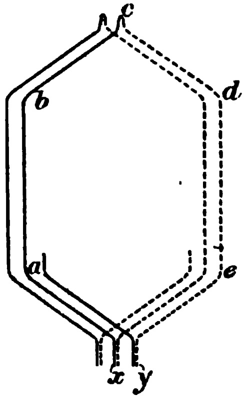


FIG. 313.

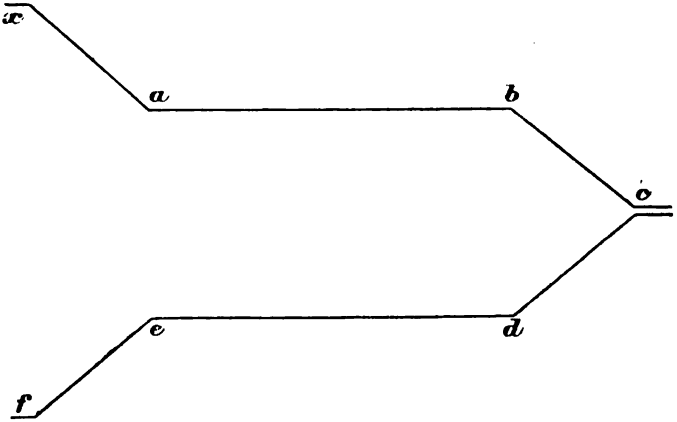


FIG. 314 —ELEMENT OF WAVE-WINDING FORMED OF TWO STRIPS.

as shown in Fig. 316. Compare the Allgemeine Company's armature, Fig. 38, p. 56. Fig. 317 is a view in the armature winding shop of Messrs. Siemens and Halske, showing how the previously formed coils are placed in the slots.

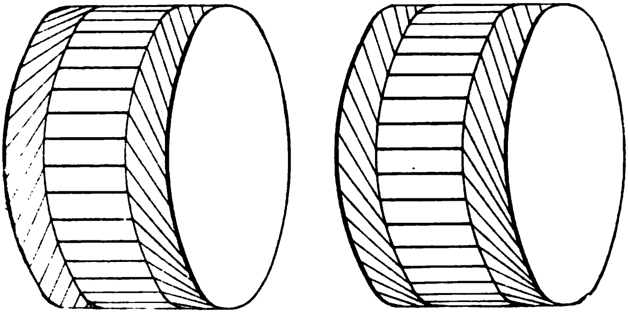


FIG. 315.—BARREL-WINDINGS, LAP AND WAVE.

The reader should here examine the armature construction of the various plates. A barrel-winding having but one layer of conductors was patented by Hon. C. H. Parsons, and independently devised by Mr. White for Clark, Muirhead and Company.

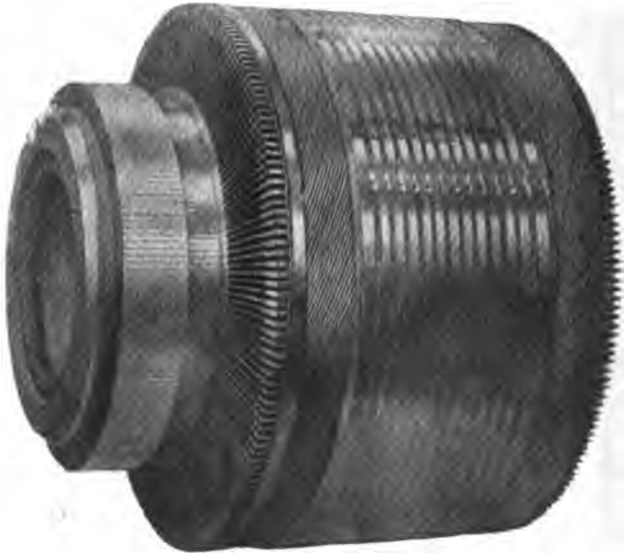


FIG. 316.—4-POLE BARREL-WOUND DRUM ARMATURE (BROWN).

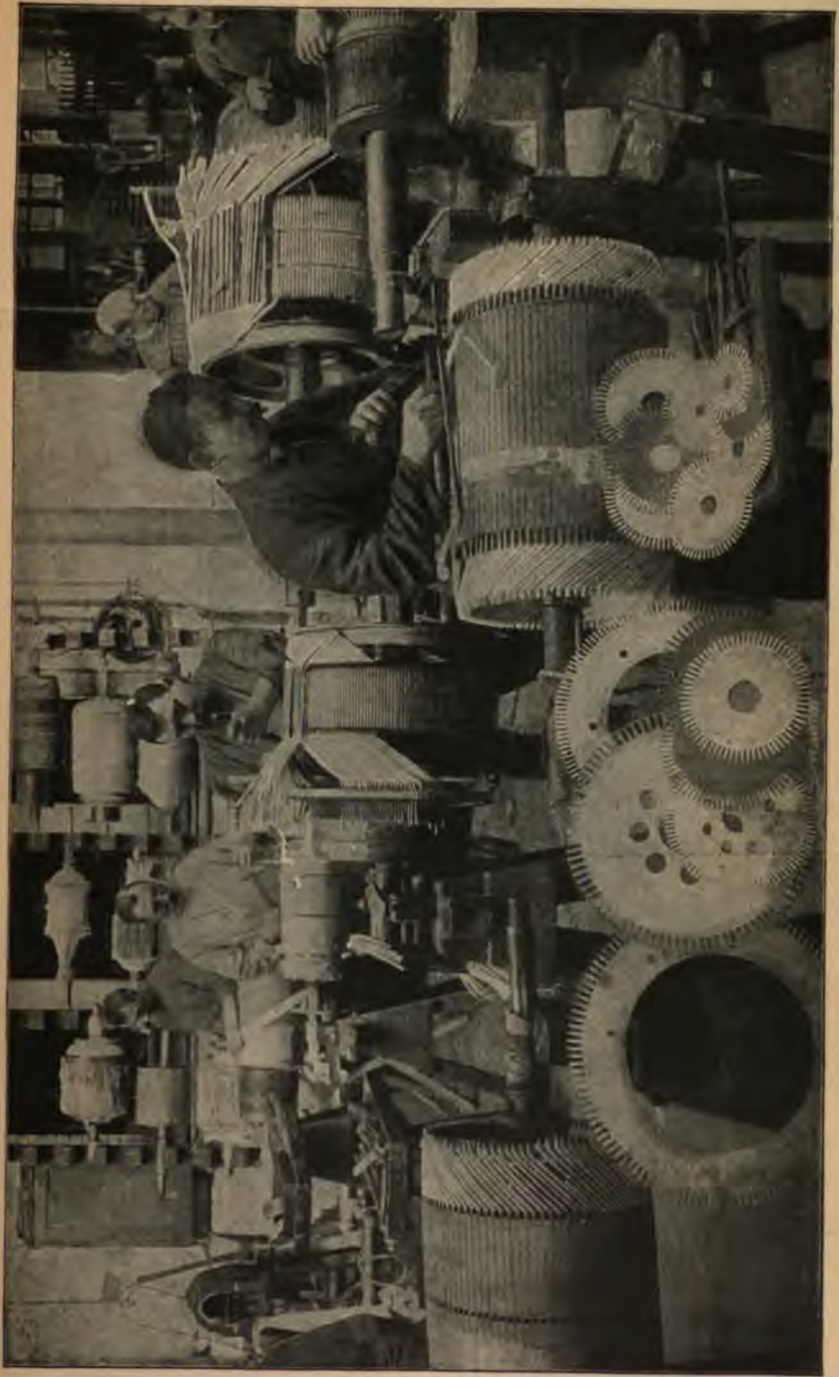


FIG. 317.—ARMATURE WINDING IN THE SHOP (SIEMENS AND HALSKE).

Bastard-Winding.—If a winding instead of being carried inward toward the shaft in evolutes, or elongated cylindrically, is bent partly inward and partly cylindrically it is called a bastard-winding. It has the effect of being somewhat shorter than the pure barrel-winding. It requires special formers for bending the conductors. Some makers construct their armatures with a barrel-winding at the commutator end and an evolute or bastard-winding at the other. Some of the West-

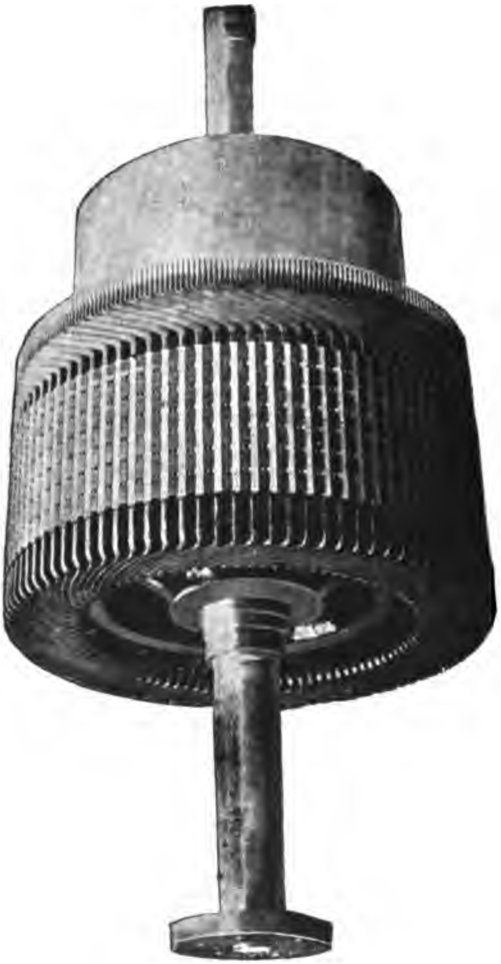


FIG. 318.—ARMATURE OF WESTINGHOUSE GENERATOR, MP. 8-560-250; 280 VOLTS, 2000 AMPERES. BASTARD-WINDING.

inghouse armatures (Figs. 318, 319) show this feature. The copper conductors are bent to shape on cast-iron formers. A barrel-winding is advisable at the commutator end because it affords room for better ventilation.

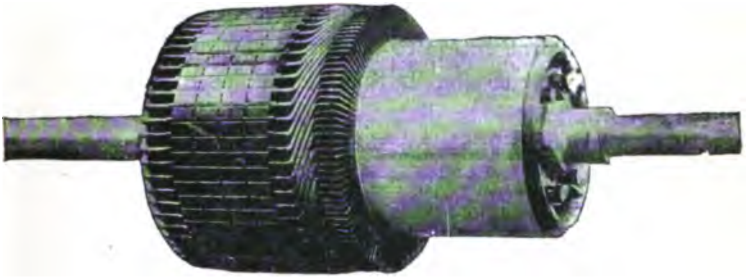


FIG. 319.—ARMATURE OF 150 KILOWATT DYNAMO (Westinghouse).

Wire-wound Drums.—So far these windings have been described as though carried out by bars connected together, but both evolute-winding and barrel-winding can be carried out with wire wound on by hand, for armatures that are not to carry very large currents. Sometimes the shaping of the coils is done during the winding, the wires being drawn into half-closed slots, and afterwards bent into the required evolute form at the ends. Cases occur where small currents are wanted at high voltages, and more than two layers of con-

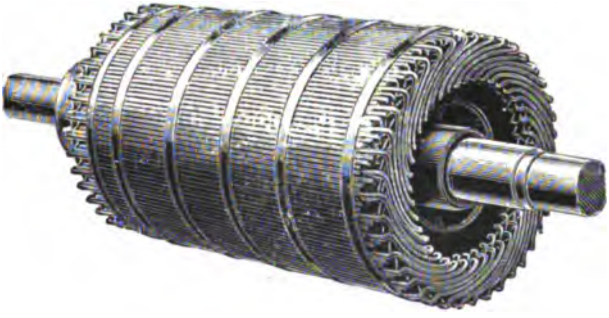


FIG. 320.—DRUM-ARMATURE BY ALIOTH.

ductors become advantageous. Fig. 320 shows an armature by Alioth of Basel with four layers of evolutes at the ends, though the core is smooth, and the conductors all in one layer outside it. With this may be compared Fig. 320, which is an armature designed by Fynn, having six layers of conductors in the slots, and a treble-deep barrel-winding. Fynn has given special attention to windings of this class in several layers, with a view to distributing them so as to avoid harmful induction in the loops. Barrel-windings with several layers of conductors are also to be noted in the Brown double-current generator Fig. 423, p. 661; and in the Oerlikon dynamo Fig. 421, p. 658.

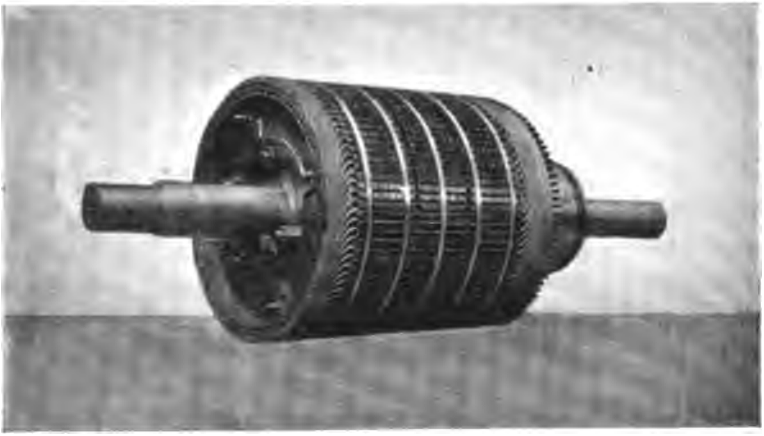


FIG. 321.—FYNN'S BARREL-WOUND ARMATURE.

Former-wound Drum-Windings.— The disadvantage of early hand-wound drums in having the winding necessarily unsymmetrical led to varieties of winding that could be separately wound on *formers* in the shop and subsequently fitted into their places on the core-body. The individual "sections" of the winding are first wound or shaped upon a frame or former, the wire being dry cotton-covered to begin with, and each such section is again separately insulated, usually by winding with dry tape, baking, varnishing, and baking again. The tape is generally half-lapped to avoid undue thickening. The earliest of such plans appears to be that of Alioth, whose German patent dates from March 1885.

Eickemeyer's method of former-winding[1] which was largely used in the States, and also in England by Mr. Parker, is illustrated by Fig. 322, which shows one of the formers for use in the winding-shop, and by Fig. 323, which shows the coil wound upon it; in this instance a coil of four turns, adapted for a smooth-core 4-pole drum.

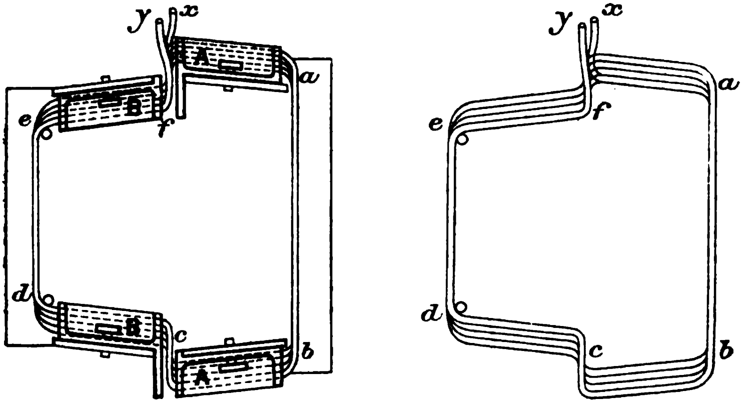


FIG. 322.—EICKEMEYER FORMER AND FORMER-WOUND COIL.

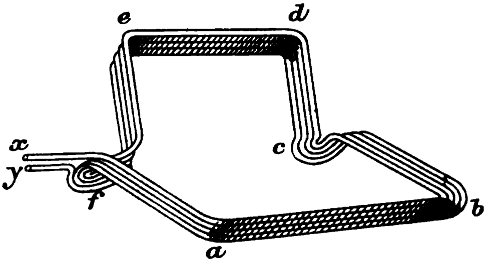


FIG. 323.—EICKEMEYER FORMER-WOUND COIL, BENT-UP.

One peculiarity of the Eickemeyer coils is that their two halves are of unequal dimensions. The part marked *a b*, which corresponds to an "upper" conductor, is longer than the part *d e*, which will constitute a "lower" conductor, the portions *d c* and *e f* act as parts of an inner layer of evolutes, and the portions *a f* and *b c* as parts of an outer layer of evolutes.

---

[1] See English patent Specification, No. 2246 of 1888.

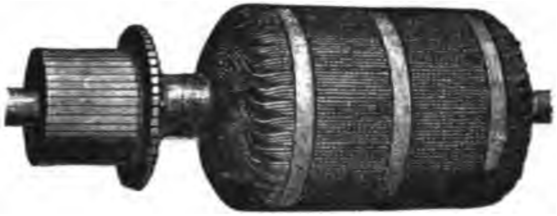
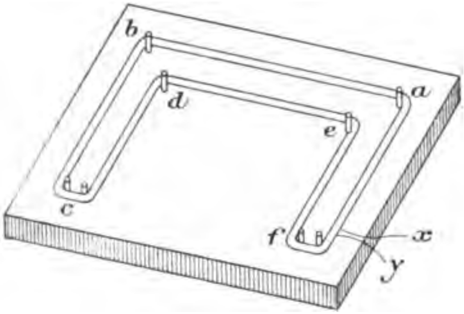
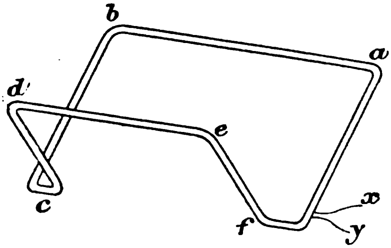


FIG. 324.—EICKEMEYER ARMATURE, COMPLETE.





FIGS. 325, 326.—EICKEMEYER COILS ON FORMER, AND OPENED OUT.

Another mode of winding Eickemeyer coils is to fix six pegs in a strong board, and wind the required number of turns of cotton-covered wire round them, as shown in Fig. 325. The coils are then over-wound with dry tape and after removal from the board are opened out to their final form, and impregnated with varnish.

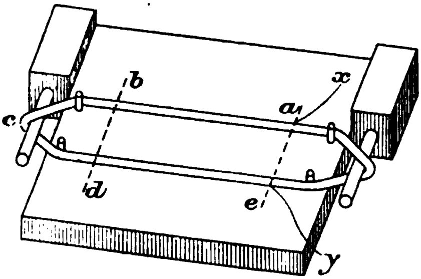


FIG. 327.—"STRAIGHT-OUT" FORMER-WOUND COIL.

What the Eickemeyer coil accomplishes for the evolute-winding can be accomplished for the barrel-winding by use of "straight-out" former coils. There are several ways of making these. A former is prepared of pegs in a block, two at the ends being fixed horizontally, as shown in Fig. 327; while four vertical pegs are arranged in two pairs. Around these a long narrow coil is wound to the required number of turns, and taped. After taping it is opened out as shown. This coil

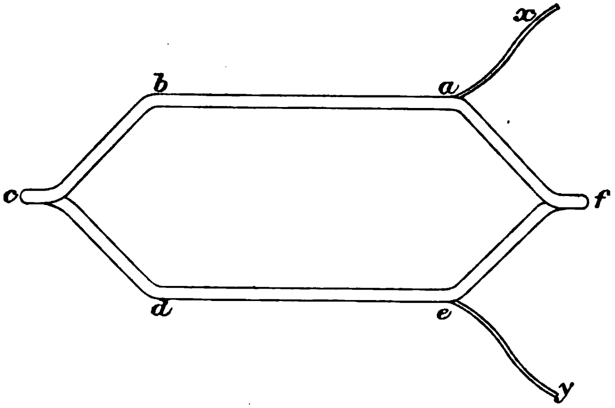


FIG. 328.—STRAIGHT-OUT COIL OPENED OUT.

differs from the Eickemeyer coils in that the two halves are of equal size *a b* and *d e*, the parts which act respectively as upper and under conductor being of equal length. The coil as shown is suitable for a wave-winding. A still simpler plan to wind the straight-out coil is to employ merely two pegs as

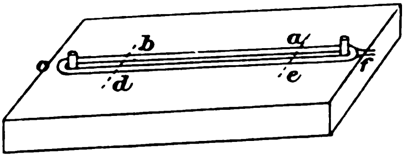


FIG. 329.—STRAIGHT-OUT COIL BEFORE OPENING OUT.

in Fig. 329; but this plan gives more trouble in the subsequent opening out.

Pictures of the various kinds of formers used in the shops are given by Fischer-Hinnen,[1] by Arnold,[2] and by Davies,[3] but it is difficult to convey the real meaning of the parts by

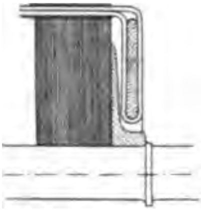


FIG. 330.—EVOLUTE-WOUND ARMATURE.

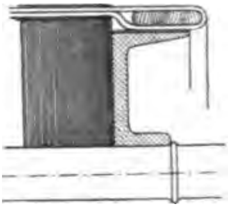


FIG. 331.—BARREL-WOUND ARMATURE.

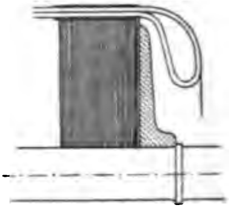


FIG. 332.—BASTARD WOUND ARMATURE.

pictures. An experienced foreman winder will be able to design his own formers as need arises. Figs. 330 to 332 give sketches of former-wound armatures of the three chief species.

Formers may also be used for moulding the shapes of single conductors for bar-wound armatures. An example of formed bars is given in the Kolben 10-pole machine, Plate XVII.

---

[1] *Continuous Current Dynamos*, London, 1899, 301.

[2] *Die Ankerwickelungen*, Berlin, 1899, 323-333.

[3] *Electrical Engineer*, May 1902.

Figs. 333 to 335 depict a small armature of the British Thomson-Houston Co. Fig. 333 shows the assembled core-body with two ventilation ducts, and having flanges to support the end parts of the barrel winding. The former-wound coils resembling Fig. 313 are in Fig. 334 partially laid in their places. Fig. 335 shows the completed armature with binding wires and commutator.

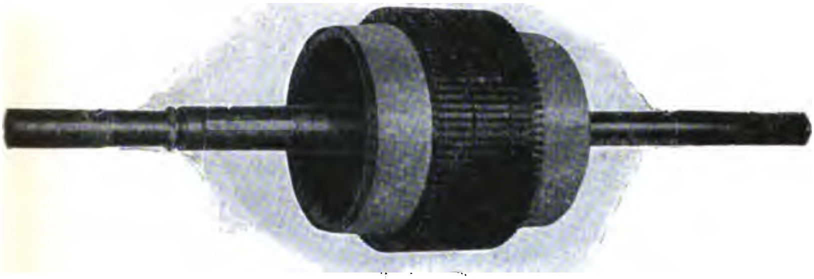


FIG. 333.—ARMATURE CORE UNWOUND (British Thomson-Houston Co.).

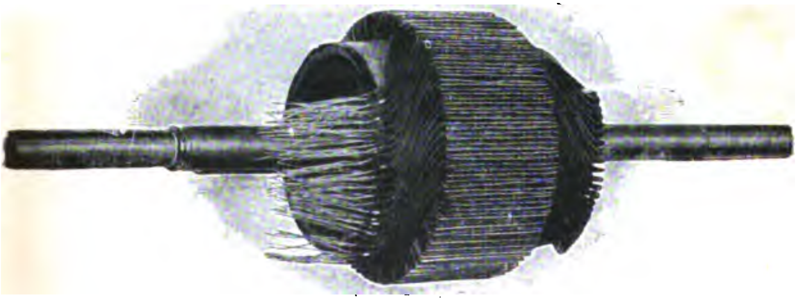


FIG. 334.—ARMATURE PARTIALLY WOUND (British Thomson-Houston Co.).

Calculations of the lengths of copper required for evolute, and for straight-out windings, have been given by G. Simmonds in the *Electrical World* for March 3, 1900, and by J. Dalemont in the Bulletin of the *Institut Montefiore*, ii. 428, 1902. Hobart has described a combination method in *Traction and Transmission*, v. 239, 1902. As a rule the barrel-winding requires less copper than the evolute-winding. For large armatures it is an approximate rule that the over-all length of a barrel-winding is equal to the axial length of the core-body plus a length equal to the pole-pitch.

Fig. 336 depicts a wave-wound drum armature of the Allgemeine Co. having former-wound coils.

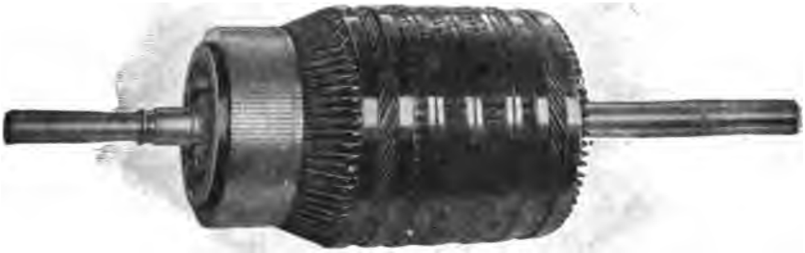


FIG. 335.—ARMATURE FINISHED (British Thomson-Houston Co.).

Evolute Connectors used as Equalizers.—The Oerlikon Co. has introduced a method of connexion which serves at the same time for equalizing without the complication of the equalizer rings described on p. 412. Assume that a barrel-winding is to be joined to a commutator by means of risers or radial connectors. Then, instead of putting for this purpose a single radial strip to join some point on the winding down to the commutator segment opposite to it, let a forked strip be applied, resembling Fig. 308, but inverted. Its upper end is united to the winding, but the two lower ends of the fork are joined to *two* segments at a distance apart equal to twice the pole-pitch, and which therefore are at equal potentials. There will thus result *two* layers of risers one behind the other as evolute spirals, and each segment of the commutator will be joined to *two* points on the winding. An example of a machine so constructed is depicted in Fig. 421, p. 658. A similar device may be applied to an armature wound with evolute connexions. To do this there is provided a set of independent evolutes united at their outer end to the winding, and which spiral round the armature to make contact at a segment distant by twice the pole-pitch from the segment which is joined to the ordinary junction of the evolute connectors. There will therefore be *three* layers of evolutes at the commutator end of the armature. This is shown in Fig. 450, p. 713.

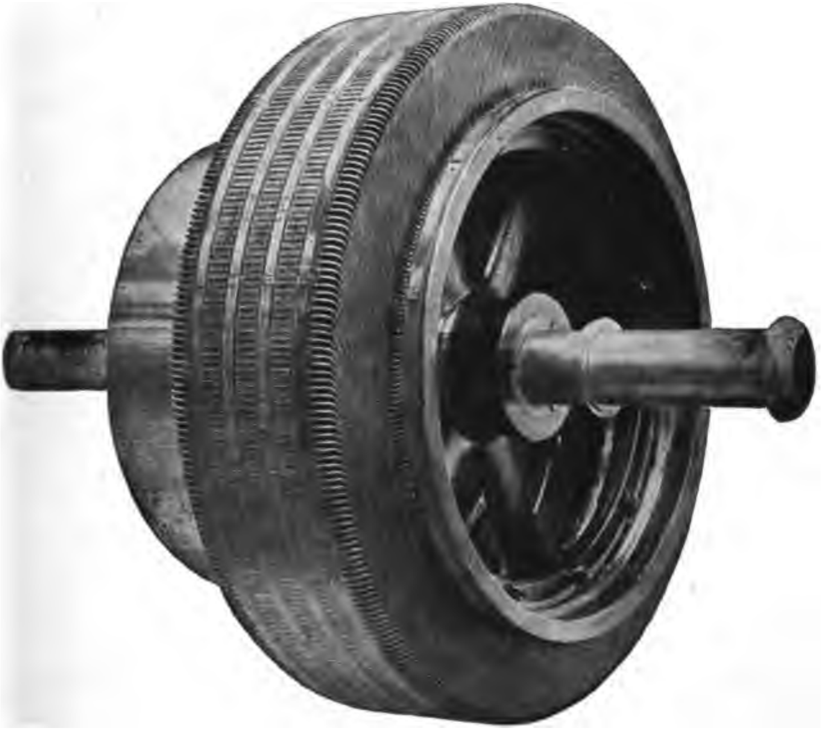


FIG. 336.—DRUM-ARMATURE OF ALLGEMEINE CO. WITH FORMER-WOUND COILS.

RING-WINDINGS.

Ring-windings may likewise be classified according to whether they are wire-wound or bar-wound. When a smooth ring-core is to be wound it is frequent to stencil upon the end faces a number of radial lines corresponding in breadth to the separate sections, so as to guide the winder in his work. With toothed cores no such plan is needed.

Ring-winding is, in general, easy; nevertheless care must be exercised. The separate "sections" of the coil are almost invariably wound on the cores separately, leaving the ends projecting, secured temporarily with a string, and these ends are subsequently connected together and to the commutator. An inexperienced workman may easily connect up wrongly; making a left-handed winding instead of a right-handed one, or *vice versâ*. Hence it is well to provide him with some such working drawing as Fig. 337, which relates to a right-handed winding having four turns in each section. The wire marked "0" is the last or outer end of the section previous to that considered. This end will eventually be brought down to a bar *a* of the commutator, and from this bar will go out the beginning or left-bottom end, marked L B, of the section in question. Looking at this diagram the winder will see that the wire L B must pass under the core to the far end and

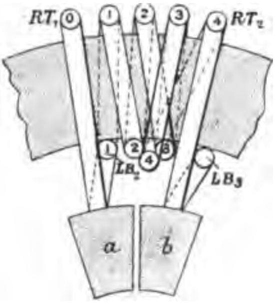


FIG. 337.—WINDING DIAGRAM, RING ARMATURE.

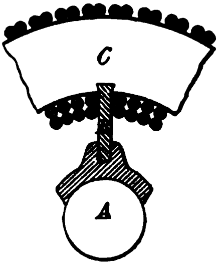


FIG. 338.—CROMPTON'S WIRE-WOUND ARMATURE.

then return over the top, thus making turn No. 1. It will then bend down to the right, be threaded through again, and make turn No. 2 ; again, and make turn No. 3 ; but as the inner space is narrower than the outer space, turn No. 4 will probably have to ride on, or partly bed between, the turns already wound. The right-top end, marked R T, will eventually be joined to bar *b* of the commutator. If the winder is shown that the right-top wire of one section joins the left-bottom turn of the next section of the commutator, he will have no excuse for mistakes. One way of arranging the windings on a ring, with two layers internally and one externally, is shown in Fig. 338.

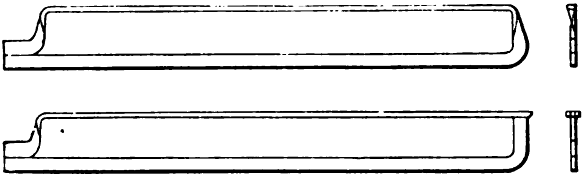


FIG. 339.—WINDINGS OF CROMPTON'S ARMATURES (1886).

For arc-lighting armatures, and in general those which have numerous convolutions of wire to each section, it is convenient to prepare the wire in separate lengths sufficient for each section, and to coil each length on small shuttles, each length being wound upon *two* shuttles, which are alternately used for successive layers. By this device both ends of the wire that constitutes a section are brought to the outside instead of one of them leading directly down to the bottom layer, as in ordinary bobbin winding.

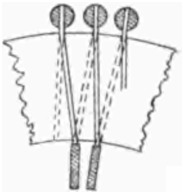


FIG. 340.

For those machines that only require one, or two, complete turns to each section, it is common to have the copper conductors prepared beforehand upon separate formers, and ready taped to be slipped on over the cores. Crompton introduced the forms illustrated in Fig. 339, consisting of drawn copper of nearly rectangular section twisted at the ends so as to pack closely in the interior of the ring. These conductors are sprung on over the ring-core, and afterwards coupled up so as to make a continuous winding. Some makers employ square or round bars for the active conductors on the periphery, with an elongated strip conductor, set on edge for the return part through the interior of the ring (Fig. 340). Where toothed cores are employed a narrow strip may be used for both the active conductors and the inactive return conductors, as the latter pack closely without iron teeth between them. Two large examples of modern ring windings will be found in the Alioth electrolytic generator, Plate XXVI., and in the Postel-Vinay 12-pole generator, Plate XX.

In the large multipolar ring dynamos with internal field-magnet and external commutator, now so much used for central stations in Germany, the windings are so constructed that their outer part serves also as commutator, as in Plate XXV. The armature consists of core-rings built up of segmental plates shown in section at *b*, Fig. 341, supported by driving-rods *a* which pass through them. After being covered with suitable insulation, the copper conductors *c d* are slipped on over them and coupled up to make a continuous spiral winding. The insulation between is usually a preparation of paper. The outer part *d* of the copper conductor is made both deep and broad, and serves as a commutator bar. The brushes (not shown) are fixed upon the projecting bar *e*, and trail on the outer periphery of the copper windings of the ring. At *f* is a lever for raising the brushes out of contact.

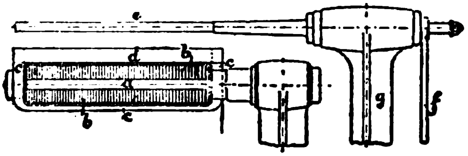


FIG. 341.—CONSTRUCTION OF GERMAN MULTIPOLAR RING-ARMATURE.

ARRANGEMENT OF CONDUCTORS IN SLOTS.

Various methods of arranging the conductors in the slots have been mentioned in the foregoing pages. In modern large continuous-current machines by far the most frequent plan is that of putting the conductors in two layers, an upper and an under, either two or else four in a slot. Former-wound coils lend themselves to a two-layer arrangement. On the other hand, former-wound coils cannot, in general, be used with any slotted armature except those having straight teeth. It is true that by grouping the conductors three or four in a slot, as in Fig. 342, or six in a slot, as in Fig. 343, T-shaped teeth can be used. It must be remembered that, owing to the magnetic shielding of the teeth the conductors are practically not subjected to any but centrifugal forces. Unless the pole-faces are laminated the top breadth of the slots must be kept very narrow; and if straight teeth are employed, they must also be kept very narrow, otherwise the high saturation that is so advantageous in sparkless commutation will not be attained. All electric and magnetic considerations point to the slots and the teeth being very narrow and very numerous. Mechanical and manufacturing considerations on the other hand demand that the slots shall be few and wide; for labour is saved, insulation becomes more simple, and a higher space-coefficient is attained. But the grouping of conductors in two layers with slots wide enough for two, three, or four conductors side by side enables wide slots to be used, with a corresponding gain. Standard practice for parallel-wound armatures is to put four conductors in a slot. But again a difficulty occurs for armatures with a series-grouping (compare

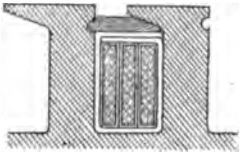


FIG. 342.

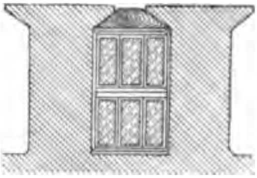


FIG. 343

p. 378) for which an odd number of commutator-segments and of "sections" is a necessity. For if the total number of conductors is to be $py + 2$, and they are in two layers, it will be impossible to put four conductors per slot into any machine, or to put six conductors per slot into a 6-pole or a 12-pole machine. In practice, series-grouping necessitates two conductors only per slot in large generators, or two former-wound groups per slot as in tramway motors and small generators. See the examples of Kolben's machine, p. 671, and Brown's high voltage machine, p. 753. Mr. Rothert[1] has given special attention to the more complicated cases and has devised special modes of winding to meet them.

---

[1] *Elektrot. Zeitschr.*, xxii. 316, 1901.

CHAPTER XV.

MECHANICAL POINTS IN DESIGN AND CONSTRUCTION.

IN Chapter XIV. are considered the mechanical modes of transmitting the power from the shaft to the armature conductors and *vice versâ*. The design of dynamo shafts, journals, bearings, pedestals and pulleys is a matter equally requiring a knowledge of mechanical principles and practice. Such standard works as Unwin's *Machine Design* and Dalby's *Balancing of Engines* should be followed. Nevertheless there are some points in which the ordinary engineering rules cease to be entirely applicable; and it is because of this circumstance that it seems desirable to give the information embodied in the present chapter.

Pressure on Bearings.—In addition to the ordinary pressures on bearings, due to weight of the shaft and its attachments, and to the lateral drag of the driving-belt, there is in dynamo-machines a third cause producing pressure, namely the actual *magnetic pull* which the field-magnets exert on the armature core. This is notably great in the case of dynamos having a single magnetic circuit. An example in which the field-magnet tends to lift the armature is afforded by those machines, such as the Edison-Hopkinson, Fig. 12, p. 26, in which the magnet stands over the armature; whilst contrary examples are furnished by machines in which the armature is above the field-magnets, as in the Kapp dynamo, Plate II. and p. 651. If the armature is perfectly centred there will always be a tendency to drag it in such a way as to make the entire magnetic circuit more compact. This can be partially obviated by placing it eccentrically, slightly below the centre of the bored polar faces in machines of the under-type, and slightly above the centre in the over-type. In Kapp's machine the downward pull is partly compensated by leaving the pole-tips wider apart below the armature than they are above it; or by using cast-iron pole-tips below and wrought-iron pole-tips above. This magnetic pull may amount to as much as four or five times the weight of the armature. To calculate the magnetic pull of any pole, we must know the density of the magnetic flux between the pole and the armature and the area. Then we may apply the formula[1]

$$P = B^2A \div 72,134,000,$$

where P is the pull in pounds weight, B the flux-density per square inch, and A the area in square inches.

Example.—In a multipolar tramway generator, the flux-density in the gap was about 45,000 lines per square inch, and the area under one pole was about 285 sq. inches. Hence the pull of that pole was at least 9900 lbs. As the flux was somewhat concentrated towards the tips of the teeth of the armature the pull would be really greater.

Centrifugal Forces.—If a mass is whirling with a radius of R inches, at U revolutions per minute around an axis, the centrifugal force is $0{\cdot}0009138\ R\,U^2$ *poundals* per pound of peripheral matter, or $0{\cdot}0000284\ R\,U^2$ *pounds* per pound of peripheral matter. This rule can be used to estimate the centrifugal forces on armature conductors.

Example.—Suppose an armature conductor weighing 0·39 lb. to be revolving at 150 revolutions per minute; the radius of the armature being 31 inches. The centrifugal force on it will be

$$0{\cdot}39 \times 0{\cdot}0000284 \times 31 \times 150 \times 150 \doteq 7{\cdot}72 \text{ lb.}$$

Gyrostatic Action of Armature.—Another point, which arises only in the case of dynamos used on shipboard and of motors running round a curve on a track, is the gyrostatic action of the revolving armature, which tends always to keep its axis pointing in the same direction. Lord Kelvin has given the following formula for the gyrostatic force on a bearing,

---

[1] See the author's book *The Electromagnet.* If B and A are given in centimetre measure, and P is described in kilogrammes, the divisor in the formula will be 226,520.

$$F = W k^2 \Omega \omega \div g l;$$

where F is the force; W mass of armature; l length between bearings; g the acceleration of gravity; ω the angular velocity of the armature, in radians per second; Ω the maximum angular velocity of roll of ship, also in radians per second; k the radius of gyration of the armature.

Example.—In a ship rolling 20°, with a periodic time of 16 seconds, a Siemens alternate-current machine running at 1300 revolutions per minute; $W = 148$ lb.; $k = 0{\cdot}7$ foot; $l = 1{\cdot}4$ foot; and $g = 32$ feet per sec., per sec. Here $\Omega = 2\pi \times \frac{20}{360} \times 2\pi \div 16 \doteq 0{\cdot}137$; and $\omega = 2\pi \times 1300 \div 60 = 136$. Then $F = 30{\cdot}6$ lb. on each bearing, alternately acting up and down at each roll, if the axis of the dynamo lies athwart the ship.

It is evident from these considerations that it would be inexpedient on shipboard to employ dynamos having armatures which resemble fly-wheels in form, if the pressure due to the weight of the armature were not relatively much greater. Mr. W. R. Kelsey has discussed the bearing of gyrostatic action on engineering design in the *Electrical Engineer* for July 1902.

Balancing of Armatures.—Running as so many armatures do at a high speed, it is absolutely necessary that they should be balanced, otherwise they will set up objectionable vibration. It is usual to balance the armature core-bodies after assembling and before winding, and again after the copper conductors are in place. For the principles of balancing see Dalby's *Balancing of Engines.*

Journals.—From what has been said it will be clear that caution must be used in applying the ordinary rules of machine design. It is usually assumed that journals are made larger for higher speeds, because of the necessity of getting rid, by the greater cooling surface, of the heat generated at the higher speed. But it is known that this assumption leads to the rule

$$l = F U \div \beta;$$

where l is length in inches; F the force (in lbs.) on the bearing; U the number of revolutions per minute; and β a constant which, according to various authorities, may vary between 66,000 and 1,000,000. With such a variation, the rule is almost useless as a guide to design; moreover it takes no account of the diameter of the journal. In all good engineering practice the ratio between the diameter and length of a journal bears a relation to the speed. For slow speeds, such as 100 revolutions per minute, the length need be no greater than one diameter; whereas for speeds of 1000 and upwards the length is five or six diameters, and in high-speed fans sometimes as much as eight diameters.

From this we get the approximate rule:—

$$l/d = 1 + 0{\cdot}004\ \mathrm{U}.$$

The rule given above, which is an ordinary one for mill-shafting, is known not to apply to crank-shaft bearings, where centrifugal force is of little importance, but where there come heavy alternately-directed thrusts and wrenches. Still less can it strictly apply to dynamo machines. In these, for the most part, the power is transmitted through a few inches of shaft from a pulley to the armature. The journal between these two parts, if the pulley is outside, is obviously sustaining a much severer wrench than the journal at the other end; it is in many dynamos made larger and longer than that at the commutator end.

In the table on the next page are given data of sundry machines.

The safe diameter for a journal to give requisite strength depends on the load tending to bend it, as well as on the mere twisting-moment that results from the power transmitted through it. The diameter of a shaft is usually calculated from the formula, applicable when there is no bending:—

$$d\ \text{(inches)} = c\sqrt[3]{\mathrm{HP} \div \text{revolutions per minute}};$$

where $c = 2{\cdot}6$ for steel shafts.

The lateral leading of an overhung pulley, due to the belt, produces a considerable amount of bending. Taking the ratios

TABLE OF JOURNAL SIZES.

Dynamo and Description of Machine.	Revolutions per minute.	Distance between bearings (inches).	Output (kilowatts)	Length *l* (inches).	Diameter *d* (inches).	Ratio *l*/*d*.
Edison (bipolar standard type)	2100 1600	18·03 34·75	1 10	2·62 6·75	0·625 1·5	4·7 4·2
Oerlikon multipolar generator	370	46·3	265	14·2	4·73	3·0
Alioth multipolar generator	280	45	210	14·8	4·4	3·36
Kolben multipolar generator	125	48	250	15·7	5·9	2·66
Gen. Elec. Co. multipolar generator.	150	42·4	125	16·5	5·5	3
Gen. Elec. Co. Multipolar generator.	257	80	875	28	12	2·33
Kolben 4-pole generator	750	22	3	11·75	3·75	3·75
Kapp bipolar generator	780	34	22·5	10 8·5	2·25 2·25	4·4 3·77
Thury electrolytic generator	250	85	350	19·7	7·9	2·5
Brown electrolytic generator	250	69	480	21·6	7·5	2·88
Gen. Elec. Co. tramway motor	640	25·8	23	7·6 5·8	2·8 2·5	2·70 2·32
Thury railway motor	525	35·4	100	9·85	3·53	2·78
Brown three-phase motor	600	32·5	75	9·2	3·3	2·78
Mordey alternator (1894)	150	100	800	45	11·5	4
Ganz marine generator	320	Direct-coupled	64	8·2	3·15	2·6
Oerlikon multipolar generator	100		500	30	8·65	3·48
A.E.G. multipolar generator	105		700	23·6	11·8	2·0
Oerlikon multipolar generator	120		250	22	7·5	2·95
Brown double-current generator	350		194	15	4·95	3·02
Parsons turbo-alternator	3000		350	12	2·3	5·2

of breadth of pulley to diameter which are usual in dynamo manufacture, it will be found that c ought to be taken as having a value variously estimated from 4·2 to 5·5. If T be the pure torque on the shaft, and if P is the belt-pull, and it is exerted at a distance a from the bearing (measured from centre of pulley to centre of bearing), the equivalent torque T′ from which to design the diameter of the shaft is

$$T' = Pa + \sqrt{P^2a^2 + T^2}.$$

Again, the spindle or shaft of a dynamo is subjected to bending by the weight of the armature, by the magnetic drag on its core, and in belt-driven machines by the lateral drag of the pulley. When running, it is also subjected to bending stresses if the masses it carries are not properly balanced. If the brasses of the bearings keep the journals in line, it is evident that all such actions tend to bend the shaft at definite points. Professor Perry calculates for discoidal armatures

$$l/d = U\sqrt{L} \div 1000;$$

and for drum- and elongated ring-armatures,

$$l/d = (U\sqrt{L} \div 3500) + 2,$$

where L is the length of the shaft between the middle points of its bearings, in inches; and U, l and d as before.

In any given case there is a certain total bending moment put upon the shaft by the weight of the armature, the pull of the belt, and the magnetic pull. Let the bending moments be plotted out as usual, and from the curve let the greatest bending moment be observed. This is inserted instead of Pa in the previous formula, and so the ***minimum*** diameter of shaft is found. Around this minimum diameter the rest of the shaft, collars, seatings with key-ways, etc., can then be designed.

Journals, if plain, are usually terminated by collars or raised shoulders, to bear against the brasses and limit end-play. In some forms of machine end-play is especially provided for, so as to cause an even wear at the commutator.

In some British machines, chiefly small ones, and others of

American make, a shaft of the same diameter throughout is used, with collars shrunk on to prevent end-play. This is not good engineering. A shaft ought to be as thoroughly designed for its work as any other part of the machine. It is well recognized in a machine design that where an axle has to bear a transverse load tending to bend it between the points of support, it must be thickest where the bending moment is greatest. One may also take as a basis of calculation the diameter appropriate at the journals (found as above) and assuming that the shaft is of circular section, calculate the diameters at the other parts by the rule that the diameter at each point should be proportional to the cube root of the bending moment at that point.[1] It must not be forgotten that where key-ways are to be subsequently cut for securing the spiders or other attachments, additional diameter must be given to admit of this without reduction of strength. An example of design is afforded by the shaft of Brown's dynamo, Plate IX.; also by that of Kapp's dynamo, Plate II.

In the first of these examples it will be observed how the armature spiders fit on over the middle portion of the shaft, and the whole is tightened up by a threaded nut against a collar on the shaft. The commutator is built up around another and shorter sleeve, which slips over a slightly reduced part of the shaft, on the other side of the collar. The pulley is within the bearing, not overhung.

In the second, the armature spider is a long sleeve of cast-iron, which stiffens the middle portion of the shaft, and is held up by a threaded nut against a collar.

For large direct-driven generators, modern practice is either to bolt the armature spider to the fly-wheel, or else to a face-plate on the engine-shaft, as shown in Figs. 442 and 445. or else to mount it solidly upon a shaft coupled to the engine-shaft; and the commutator shell is also usually bolted to the armature spider instead of being mounted on a separate spider.

In Plate XXVII. are given the designs of a number of shafts. In these the journals are marked J, the seatings for armature bosses A; seatings for pulleys P; seatings for commutators K; oil-ejecting collars O.

---

[1] See Unwin's *Machine Design*, vol. i. p. 264 (edition 1901).

Bearings and Pedestals. — Bearings for dynamos are always made divided, so that the armature can be lifted from its bed, and usually with steps of brass or gun-metal seated in an appropriate pedestal. Those who are not familiar with this elementary part of machine design should examine the drawings of the pedestals and bearings of various machines; particularly those of Brown's dynamo, Plate VII.; and those of other Plates. Often the pedestal is made in two parts bolted together; the joint occurring at the level of the under side of the armature to admit of the latter being withdrawn, and affording a resting point during removal. Where long bearings are used they are occasionally made of cast-iron instead of gun-metal or brass. More often a soft-metal bearing is used; or rather a soft alloy, such as Babbitt's metal or "Magnolia" metal, is used as a lining for a step of gun-metal or cast-iron; such antifriction metal being cast into shallow recesses formed for that purpose in the hollow of the step. In the case of dynamos mounted on the end of the

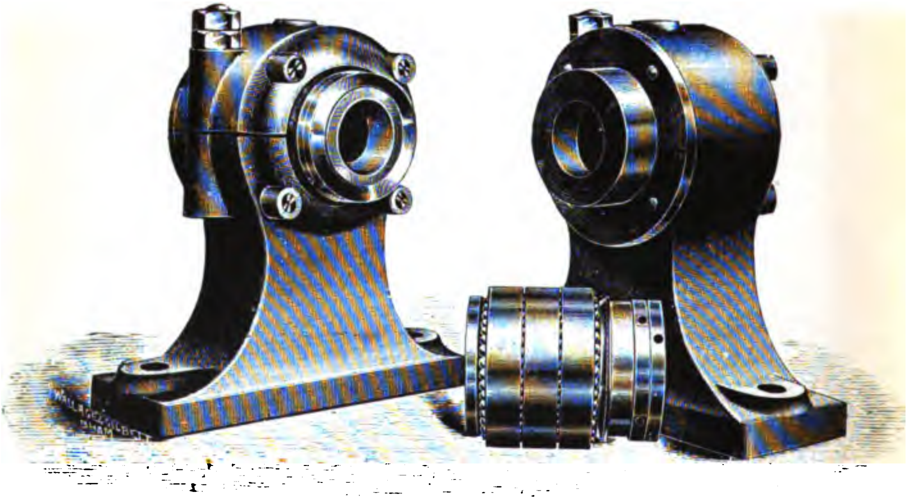


FIG. 344.—BALL BEARING (AUTO MACHINERY COMPANY).

engine shaft, for direct driving, it is usual to have only one dynamo bearing at the outer end. See examples in Plates

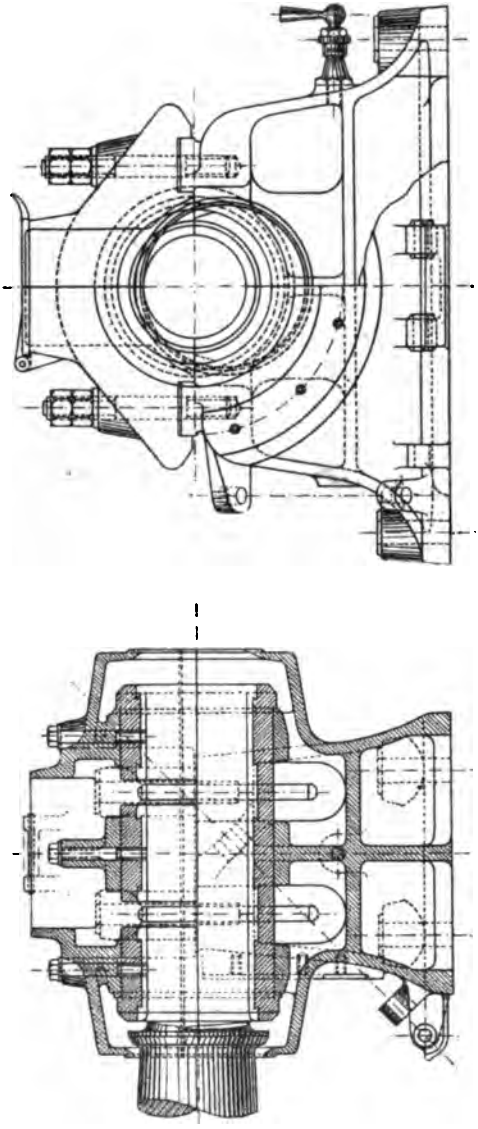


FIG. 345.—BEARING OF OERLIKON GENERATOR, MF 12-500-100.

V. and XIX. The Postel-Vinay generator, Plate XXI., is overhung and has no outer bearing.

Fig. 345 illustrates a bearing from a 500 kw. generator by the Oerlikon Maschinenfabrik; it is provided with self-oiling rings.

Vertical shafts for dynamos driven by water turbines need special designs for bearings. They were first introduced by Brown about 1890. Several examples are given in the present book.

Ball Bearings.—With the introduction of machinery of precision for making steel balls for antifriction bearings, the use of the latter for dynamos has been coming into favour. Fig. 344 gives the view of a bearing of this class, and shows the disposition of the balls between the revolving liner and the outer stationary rings. For motor-generators, where there is no lateral drag due to belts, these bearings have been found excellent. Roller bearings have some advantage in large machines. See Bayley Marshall, *Rep. Brit. Assoc.* 1897.

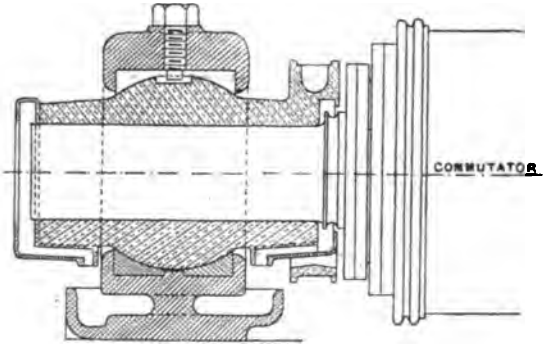


FIG. 346.—SPHERICAL BEARING OF GOOLDEN DYNAMO.

Thrust Bearings.—In all dynamos with disk or discoidal ring-armatures, end-play is inadmissible; and thrust-bearings must be provided similar to those used on screw propeller shafts with raised collars on the journals. Or, instead, the shaft may be constructed with shoulders somewhat deeper than usual at the journals, to bear against the brasses. The bearings of steam-turbine alternators, running at very high speeds, deserve special notice.

Spherical Bearings.—With all long bearings it is of great importance that they should not only be exactly concentric, but that they should also be accurately in line. To permit the steps to adjust themselves to perfect alignment it is now a frequent practice to provide them with a spherical seat; that is to say, a spherical or nearly spherical shape is given to the enlarged central portion of the bearings, and this spherical portion is provided with a soft metal seat on the pedestal.[1] Fig. 346 gives a design by Mr. Ravenshaw.

Lubricators.—Provision must be made for lubricating bearings with a due supply of oil or grease, and arrangements to prevent waste and spilling. It is usual to provide an oil-well in the hollow casting of the pedestals, into which the oil drains from the ends of the brasses. Sight-feed lubricators which supply the oil visibly drop by drop are undoubtedly best for ordinary machines. Such a lubricator is illustrated in Fig. 347. The lever C at the top closes the feed of oil when the machine is not wanted to run. The collars A and B regulate the rate at which the oil flows down to drop through the tube-sight below. For ship dynamos special forms that cannot spill oil are preferable. It is usual to provide a collar on the journals to collect and throw off the oil centrifugally, the lips of the bearing being carried (as shown in Fig. 346 above) beyond the brasses, and provided with a re-entrant rim which catches the oil and returns it to the well below. Sight-drain lubri-

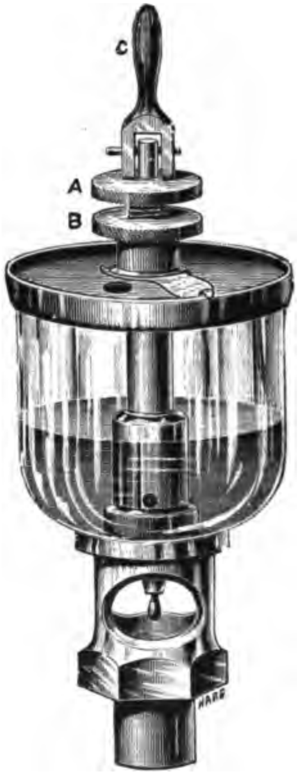


Fig. 347.—Visible Drop-feed Lubricator.

---

[1] See paper by Mr. Coleman Sellers, in *Journal of Franklin Institute* for 1872, or *Engineering*, xv. 17, or the figure in Unwin's *Machine Design*, i. p. 310.

cators which permit the oil that flows from the bearings to drop visibly are in some cases preferable. For large dynamos, where there is great weight on the bearings, special precautions have to be taken, as in the lubrication of the bearings of propeller shafts. Oil is supplied under pressure, sometimes from two independent sources, to prevent risk of failure. Such arrangements are the more needful in the case of dynamos, because the motion is one of pure rotation, the shaft not being subjected, like the crankshaft of a steam engine, to alternate lateral thrusts, which help to work the oil in under the journals. Sellers has proposed a double lubrication[1] as a safeguard. The ordinary lubricator supplies oil at the centre of the bearing, and the top brass is provided near each end with a cup containing a stiff mixture of tallow and oil, which only melts in case the bearing heats from failure of the ordinary oil supply. Self-lubricating devices are now very general, an oil-well being provided in the lower brass, into which dips a collar on the journal, or a metal ring running loosely over it, or even a mere ring of felt. Fig. 348 represents the self-oiling arrangement used in their small motors by the Crocker-Wheeler Co. of New Jersey. Some makers provide spiral grooves in the soft-metal lining of the bearing, so that the oil brought up by the ring is distributed along the journal.

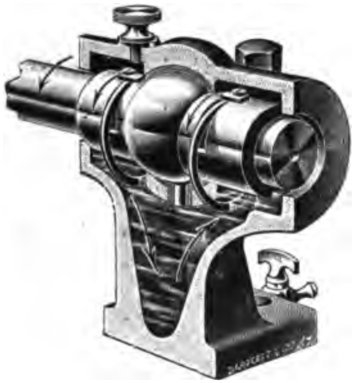


FIG. 348.—BEARING WITH SELF-OILING RINGS.

For dynamos and alternators of the "umbrella" type, with vertical shafts for use with turbines, very special oiling arrangements must be used on account of the very great weight on the bearings (see Plates XIV. and XXIX.). Arrangements are made in all large machines of this type to take a large portion of the dead weight off the bearing surfaces, by means of hydraulic floats, or in some cases by applying electromagnets to produce an upward pull. In the case of the great Niagara alternators, the lubrication is effected by oil placed in a large cast-iron cup several feet in diameter attached to the shaft below the bearing. Into the oil dips a stationary tube, up which, when the cup revolves, the oil rushes to the top of the bearing. A cold-water circulation is provided for artificial cooling.

---

[1] Unwin's *Machine Design*, i. p. 310.

Keys and Feathers.—Keys for securing the armatures and pulleys to the shaft should be of the sunk or flat type, not of the saddle type, which is less reliable. The rules for keys are as follows: b meaning breadth; t thickness; and d diameter of the eye of the hub, all in inches—

$$
\begin{aligned}
b &= \tfrac{1}{4}d + \tfrac{1}{8}'' ; \\
t, \text{ for sunk keys} &= \tfrac{1}{10}d + \tfrac{1}{8}'' ; \\
t, \text{ for flat keys} &= \tfrac{1}{11}d + \tfrac{1}{16}'' ;
\end{aligned}
$$

For small machines these numbers are needlessly large. Where two or more feathers are used on different sides of the shaft, the breadth of each may be somewhat less than this. Where two feathers are used it is better to place them 120° apart than at 90°, as so often is the case.

Pulleys and Belts.—There is no need to give special rules for these, as the ordinary rules for running machinery apply.

Bed-plates.—In designing bed-plates it is usual to save weight of metal by coring out and leaving stiffening ribs and flanges. All this is quite right except in those cases where any part of the bed-plate serves also a magnetic purpose and constitutes a part of the magnetic circuit. For example, in the Kapp dynamo, Plate II., the bed-plate serves partially as a yoke for the field-magnet; and in the "Manchester" type of dynamo, Fig. 13, the part of the casting which passes under the armature must be left solid. British makers usually design bed-plates of box-pattern. In the case of machines with drum or cylindrical-ring armatures it is convenient to be able to withdraw the armature longitudinally by removing one pedestal, which therefore should be a separate casting.

In that case, for machines of the over-type, it is convenient that the pedestal should be made removable down to the level of the under side of the armature, so that when the upper part is removed the stump may form a convenient resting place for the armature in removal. A case is shown in Fig. 456, p. 720, and in the Kapp dynamo, Plate II.

Couplings.—When dynamos are driven without belting from the steam engine on the same bed-plate, it is frequent to connect their respective shafts by a coupling. Of these devices there are several special patterns, such as Brotherhood's, with a connecting part of leather, and Raworth's with flexible steel bands, admitting of a certain amount of play if the two shafts are not in exact alignment. The coupling is occasionally so constructed that it also insulates the engine from the dynamo. In the case of large modern generators, solid face-plate couplings are usually employed. See Plate XXVII.

Where fly-wheels are mounted on the same shaft they should be as near the armature as possible, in order that in the event of any sudden change of load (as may occur from a short-circuit), the fly-wheel may as directly as possible take up the thrust. The arrangement, once fashionable, of putting the fly-wheel at one end of a long crank-shaft and the dynamo at the other, is almost the worst possible. In some cases—example, the tramway generators of the English Electric Manufacturing Co.—the armature boss is bolted direct to the fly-wheel.

CHAPTER XVI.

COMMUTATORS, BRUSHES AND BRUSH-HOLDERS.

DYNAMOS for furnishing continuous currents require a *commutator* (sometimes called a *collector*) and *brushes* to collect the current. The essential action of these organs has been already described (see pp. 45 to 53); and the causes that give rise to sparks are discussed in Chapter X. We have now to consider the design and construction of these organs.

We may distinguish three types of apparatus for collecting the currents from dynamo machines.

I. Continuous-current dynamos with closed coil armatures as used for general lighting and power requiring a constant potential, are furnished with a commutator of the Pacinotti type, that is to say, consisting of a considerable number of parallel bars secured around an insulating hub, and presenting a cylindrical surface, against which press a pair (or usually more than one pair) of brushes or sets of brushes.

II. Continuous-current dynamos of the open coil type, as used for arc lighting, and giving a constant or nearly constant current, are provided with a commutator consisting of a comparatively small number of segments, each covering a considerable angle, and separated by air-gaps from one another. These are described in Chapter XXII.

III. Alternators with revolving armatures need a pair of collecting rings of metal, each provided with one or more brushes, or some analogous device to form a sliding connexion with the circuit. Alternators with revolving field-magnets of which the winding also revolves, need a similar device to convey the exciting current to the moving coils.

Commutator Segments.—The number of bars of the commutator depends on the number of "sections" in which the armature winding is grouped. In the case of parallel-wound armatures, where there are as many sets of brushes as there are poles, the current to be collected at each set of brushes is equal to the total current divided by the number of pairs of poles. Thus, in a 10-pole machine with an output of 800 amperes, there will be five positive sets and five negative sets of brushes, 160 amperes passing in or out through each set. Increasing the number of commutator segments per pole diminishes the tendency to spark (page 255); and lessens the fluctuations of the current (page 288). There are, however, two practical reasons against making the number of bars (and therefore of the windings) very great. Increasing the number increases the cost. Again, in large machines having but one loop of the armature winding from each bar of the armature to the next, the number cannot be greatly increased without exceeding the voltage desired. For example, in a bipolar Edison-Hopkinson machine for an output of 1100 amperes at 105 volts, only 43 convolutions are required. On the other hand, it is found for small dynamos, that if the number of bars is increased, each bar becomes too thin. The width of segments at the face, averages about 0·3 inch. Small commutators for use with copper brushes sometimes have segments as narrow as 0·2 inch. Again, the bars should be of a length proportioned to the number of amperes that is to be taken off at them. They are seldom less than 1 inch and seldom more than 20 inches long. Modern practice varies somewhat, but it may be fairly represented by some such figure as 1·2 inches for every 100 amperes (per brush-set), if copper brushes are used, or 4 inches if carbon brushes are used.

Commutators for use with copper brushes may, therefore, be made somewhat smaller than those for use with carbon brushes. With copper brushes, moreover, higher peripheral speeds are admissible than would be possible for carbon brushes, for which 3000 feet per minute is the limit.

Number of Segments.—The proper number of segments K is determined by the winding of the armature, and therefore by the output and voltage of the machine. If the suitable number of average volts per segment e_k is known from experience, one can at once estimate the value of K by dividing the prescribed voltage E of the machine by e_k, and then multiplying (for parallel-wound armatures) by the number of poles p.

$$K = E \times p \div e_k;$$

or, for armatures with series-parallel winding, having c circuits

$$K = E \times c \div e_k.$$

Now experience gives the following values of e_k:—

For machines working at	Average volts per segment.	Average segments per pole or per circuit.
500 to 550 volts	5½ to 15	35 to 100
200 to 220 volts	4 to 10	20 to 55
100 to 120 volts	3 to 5	20 to 35

The matter is, however, influenced by the current to be collected, for if the current to be collected is less than 100 amperes the value of e_k may be taken higher, but under no ordinary circumstances to exceed 25 volts.

Arnold's Rule.—To fix the proper value of K, Arnold has given the rule that it must *not be less than* from 0·037 to 0·04 times the product of Z into the square-root of the current carried by one circuit of the armature. For example, in a 4-pole machine with 4 circuits, each carrying 100 amperes and having 336 armature conductors, Arnold's rule would assign, as the minimum value of K, $0{\cdot}037 \times 336 \times \sqrt{100} = 123$. The machine actually had 168; two conductors united into one loop constituting the element of the winding. Had the element chosen been of two loops with 4 conductors, the number of segments would have been 84 only, and the machine would probably have sparked. Nevertheless it is certain that good machines have been constructed for which the constant was lower than 0·037, even as low as 0·025.

In practice K is equal to Z divided by some whole number most commonly 2 or 4, but occasionally in small machines a still larger number. The number cannot be 3 or 5, because these numbers would imply that there are 1½ or 2½ loops in the element of the winding. The only way of attaining such a ratio is by making alternate elements of different numbers of loops. For instance, to get 1½ loops on the average, the first element may consist of 1 loop, the second of 2, the third of 1, the fourth of 2, and so on.

Size of Commutator.—The appropriate size of commutator can be determined as follows:—Writing b for the width of the segment at the face, and l_k for the useful length of the segment, d_k for the diameter of the commutator, a for the current-density at the brush contact-face, and ξ for the number of segments covered at one time by one brush, we have the following equations:—

$$E = e_k \times K \div p; \qquad [1]$$

$$C = b \times l_k \times \tfrac{1}{2} p \times a \times \xi \text{ (neglecting thickness of insulation)}; \qquad [2]$$

$$K = d_k \pi \div b. \qquad [3]$$

Multiplying together the first and second equations and substituting the value of K we deduce

$$d_k \times l_k = \frac{E\,C}{\tfrac{1}{2} a \pi \xi e_k}. \qquad [4]$$

If a be taken at 40 amperes per square inch and ξ as 3, this becomes

$$d_k \times l_k = E\,C \div 60 \pi e_k. \qquad [5]$$

Another useful rule as to dimensions is, that it is always well to make the commutator of large diameter, provided that the peripheral speed does not exceed 3000 feet per minute. A frequent proportion chosen is ¾ of the diameter of the armature. If the peripheral speed in feet per minute is called v, we get the rule

$$d_k = \frac{12\,v}{\pi \times r.p.m.}; \qquad [6]$$

And, assuming as a moderate peripheral speed, 2600 feet per minute, we get

$$d_k = 10{,}000 \div r.p.m. \quad . \quad . \quad . \quad . \qquad [7]$$

Another trial value of d_k, if K is known, is :—

$$d_k = 0{\cdot}3 \times K \div \pi. \quad . \quad . \quad . \quad . \qquad [8]$$

Example.—MP 6—150—450—250_v—600_A. Taking e_k at 6 volts per segment the formula [5] gives 132 as the product $d_k \times l_k$. To separate this into factors, as the revolutions per minute are 450, and as a peripheral speed at the commutator face of 2600 feet per minute is not too high, d_k works out from formula [6] as 22 inches, making $l_k = 6$ inches. If, therefore, the brushes in each set were close together the length of the working face would be 6 inches; but as some space is necessary between the brushes, and also at the ends, the working face must be made a little longer. In the actual machine (Scott and Mountain, p. 582) the dimensions were $d_k = 21$, $l_k = 7{\cdot}5$, and K was 248.

Requirements in Design.—The construction of commutators must meet several difficulties. The segments must be adequately insulated from one another and from the supporting shell or sleeve. They are subject to considerable centrifugal forces, yet they cannot be screwed down into their places, for that would destroy their insulation. They must therefore be clamped firmly in their places by end clamping-rings or clamping segments protected by insulating layers, and as all insulation is unmechanical and unable to bear tensile stresses, these layers must be so interposed as to be subject to compressing stresses only. It is of the utmost importance for good and sparkless commutation that no segment should by any possibility rise out of its place through centrifugal force or through expansion by heating. Hence, the clamping devices must be strong and incapable of working loose. The mode of attachment of the bars should also be such as to make the greatest amount of length available. They should also be of considerable radial depth, to allow for wear, as the commutator needs to be turned down from time to time to preserve cylindricity. The usual dimensions are from 1 inch to 2 inches deep. As for the material most makers use, for small machines, hard drawn copper, made in long lengths of the proper section and cut off to the length required, or, where the design involves projecting lugs or much shaping, drop-forgings of copper are used which are of the proper section and only need a light cut at the ends to finish them to the proper shape. Cast-copper and phosphor-bronze bars are to be deprecated. They are more costly as they must be machined to the proper section, and they vary in hardness and cause the commutator to wear unevenly. Drop-forgings of varied shapes and sizes are now articles of commerce.

In order to secure good fit, the cross-section of the copper-segments should taper properly according to the number that are to be taken to make up the whole circumference. It is obvious that if K = 360, each segment should have a taper of 1° between its faces; if K = 36, each would need a taper of 10°. It is not practical to use a mica insulation that has not parallel faces; any defect in the taper of the copper segments cannot be made good by packing with mica; but when the number of segments exceeds 150, segments of the same angle may be used for two segments more, or two segments fewer than the exact number. Thus a segment made with the exact taper to suit for K = 220 might be used for K = 222, or K = 218. The manufacturers of commutator segments issue tables of angles and chords to facilitate precision. Such a table is given in *Electrical Review*, xli., September 10, 1897, p. 335. Thus for K = 248 the angle of taper of the segment is 1° 27′, and the chord of this angle, for the radius of 1 inch, is 0·0253 inch. To determine the thickness of the segment the value of the chord must be multiplied by the radius of the commutator, and the thickness of the mica then subtracted. Thus, for the above example, if $d_k = 21$ and the mica used is 36 mils thick, the thickness of the segment at the face will be $(0{\cdot}0253 \times 10{\cdot}5) - 0{\cdot}036 = 0{\cdot}2296$ inch. Or, again, if the thickness of the segment and the thickness of the mica are given, the diameter may be calculated from the value of the chord given in the table thus:—Add together the thickness of the segment, and that of the mica. Double the sum and divide by the chord. For example, if the segment be 0·2296 inch thick and the mica 0·036, and the chord of its taper is 0·0253, the diameter will be $2(0{\cdot}2296 + 0{\cdot}036) \div 0{\cdot}0253 = 21$ inches.

Insulation.— It is needful to have a good insulation between each bar and its neighbours, and a specially good insulation between the bars and the sleeve or hub around which they are mounted, and also between the bars and the clamping devices that hold them ; for the difference of potential is small between neighbouring bars, and much larger between the bars and other metal-work. The insulating material must not absorb oil or moisture : hence asbestos, plaster and vulcanized fibre are inadmissible. The end insulation rings may be of micanite or the preparation of paper pulp known as " press-board " or " press-spahn." The conical rings are usually built up of micanite (mica and shellac) moulded while hot under pressure to the correct shape ; more rarely the developed surface is cut out of the flat micanite sheet, and bent to shape. Fig. 349 depicts a conical end-ring of micanite cut away to show its section. Commutators with air-gaps between the bars have been used. But with air-insulation there is some trouble in keeping the gaps from being filled by metallic dust from the wearing of the brushes. It is of some importance that the mica selected for insulating the bars from one another should be soft enough to wear away at the same rate as the copper bars, and not project up above the cylindrical surface. Amber mica of a soft and rather cloudy quality is preferred to the harder clear white or red Indian mica. The usual thicknesses are as follow :—

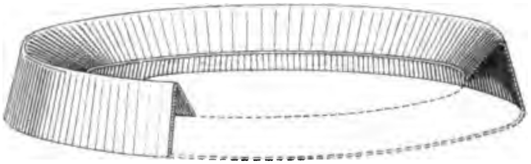


FIG. 349.—COMMUTATOR END-RING OF MICANITE.

Voltage of machine.	Thickness of Mica.	
	Between neighbouring segments.	Between the segments and the shell, and between segments and clamping-rings.
125 volts or under	0·020 to 0·030	0·060 to 0·100
250 volts	0·025 to 0·036	0·060 to 0·120
1000 volts	0·030 to 0·060	0·100 to 0·160

The micanite insulation used at the ends is not infrequently backed up with some thicker layer of a less expensive and less highly insulating preparation, such as papier-mâché or ambroin. An example of this occurs in the commutator figured in Plate XI. There is some advantage in arranging that the metallic clamping-rings shall not, as in Fig. 350, come up level with the face of the segments, for it is then difficult to prevent conduction, or even arcing from occurring by dust accumulating at the edge of the mica. There is preferably either a raised ridge of insulation as in Figs. 351 and 352, or else the working face of the segment should extend to the end of the cylindrical surface, as in Plate XXIII.

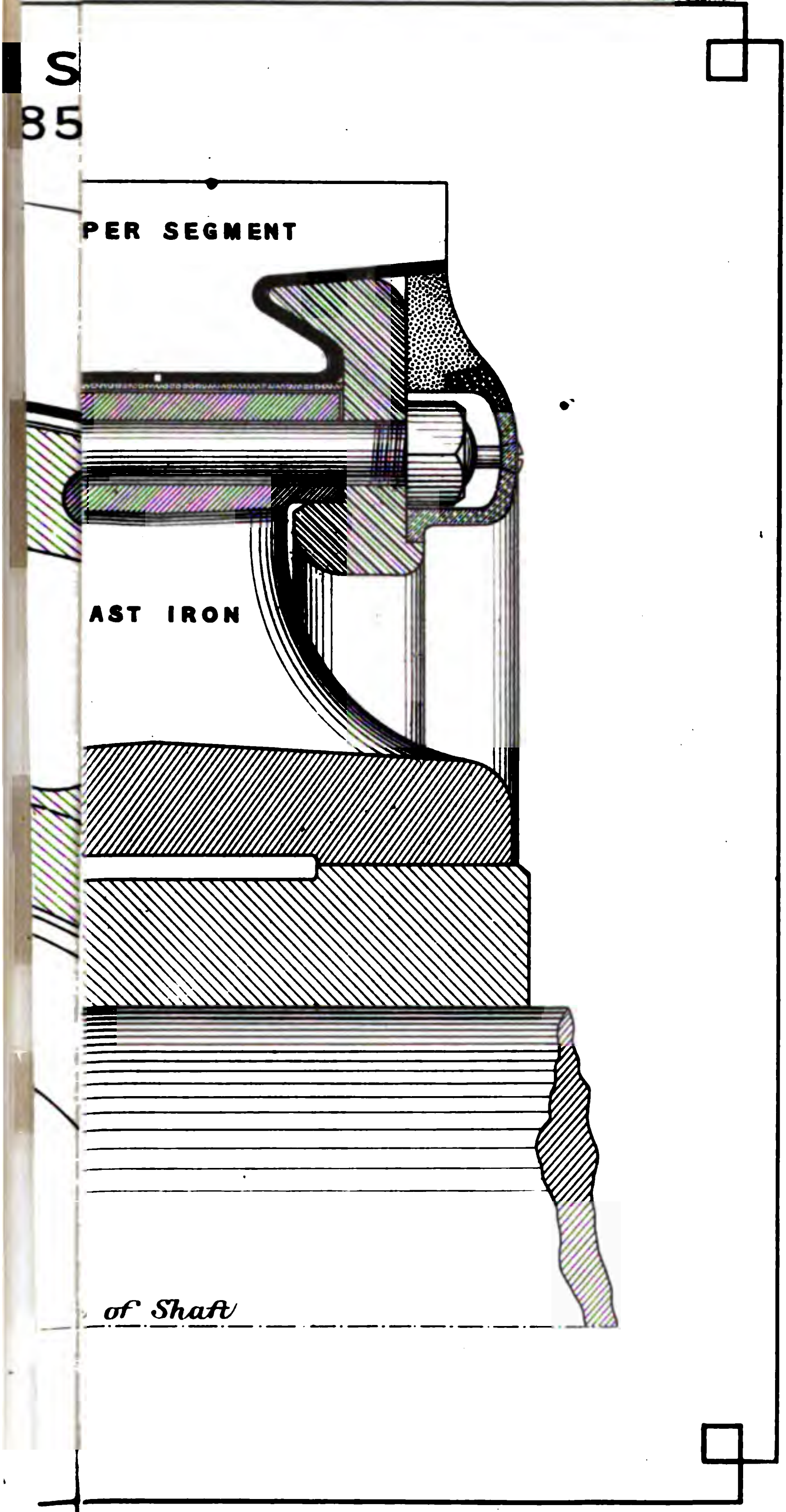
Construction of Commutators.—For small machines a common construction is that shown in Fig. 368. The segments are secured between a bush or hub and a clamping-ring, the ring being mounted on the hub and forced to grip the bars by means of a nut on the hub or by bolts passing through the ring and hub. The ends of the bars are bevelled so that the ring and bush draw the segments closer together on tightening.

The hub in small machines is usually of cast iron keyed to the shaft; but in large machines the commutator is built upon a strong flange-like support or shell bolted to the armature spider, thus leaving a clear air-way to the armature.

When drawn copper strip is used the design should be such that the available surface for the brushes takes up nearly the whole length of the bar, and the bevelled ends should be as simple as possible; with drop-forged segments this is not so important.

S

85



Thoˢ Kell & Son Lith.

In the construction shown in Fig. 350, the bars are clamped in place by being shaped with projecting snugs which fit at one end into a groove in a gun-metal sleeve, and at the other under an external clamping-ring which is forced over their bevelled ends by a large screw-washer. The clamping-ring in this case reduces the available surface for the brushes.

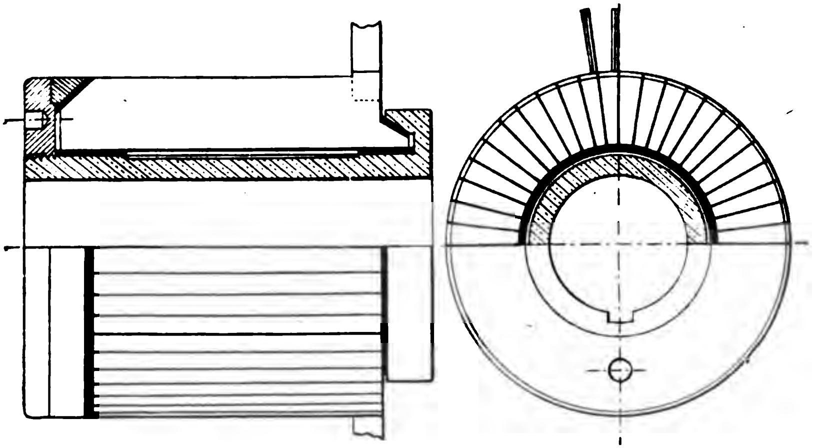


FIG. 350.—SECTION OF COMMUTATOR (PATERSON AND COOPER).

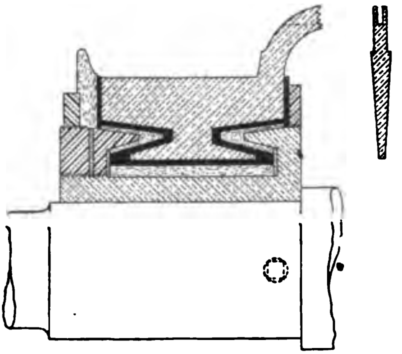


FIG. 351.—COMMUTATOR OF TRAMWAY MOTOR.

Fig. 351 depicts a modern commutator as used in tramway motors, having a diameter of 6 inches, and a working face about 2¼ inches in length. In this case special drop-forgings of copper are used, clamped below to a sleeve of bronze. The insulation is particularly carefully carried out with mica backed with thicker layers of paper preparation.

A construction which is illustrated by Fig. 353 relates to a four-pole machine with only two sets of collecting brushes. Here also the bars of the commutator are assembled around a sleeve fixed on the shaft, but are so arranged that their whole length is available for contact with the brushes; being held in position at their ends, with insulating rings, between V-shaped nicks in the bars and the clamping pieces which enter them, as in Fig. 368.

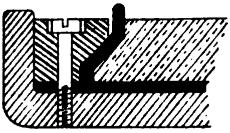


FIG. 352.—DETAIL OF SEGMENTAL CLAMPING-RING.

A very similar arrangement obtains in Kapp's dynamo (Plate III.), in which the clamping nicks in the ends of the bars are made deep; the end insulation being effected by three rings of vulcanized fibre, one flat, the other two conical, which fit into the ends of the assembled bars.

For larger machines, the commutator segments are assembled upon a special pulley-like hub, which is either keyed to the shaft, or bolted to the armature hub, and they are securely held in place by clamping-rings, usually built in segments, so that in case of need a portion of the commutator may be dismounted and replaced without dismounting the whole. Fig. 352 illustrates a modern example. Examples of segmental construction may be seen in several of the Plates. Special attention should be given to the constructions shown in Figs. 421, p. 658, and 450 (Oerlikon Co.), Plate XI. (Parshall), and Plate XXI. (Kolben). For machines having a large output of current, and a limited number of poles, commutators of great length are necessary; and in such special means must be devised for holding the segments that, in their expansion with heat they may not assume an irregular surface. Fig. 354 depicts a construction due to the Oerlikon Co., for a 6-pole machine of 1500 amperes, collecting therefore 500 amperes at each set of brushes. The length of the working face is 18½ inches. In commutators of still

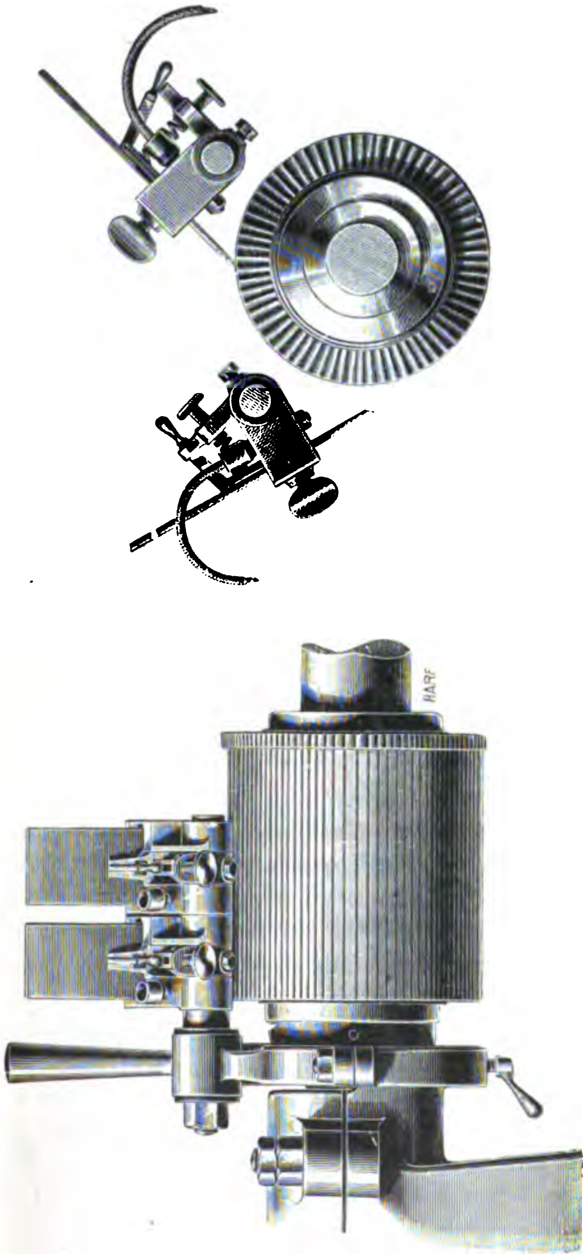


FIG. 353.—COMMUTATOR AND BRUSH-HOLDERS OF GÜLCHER CO.'S 4-POLE MACHINE.

greater length some means must be taken to support the middle as well as the ends of the segments. Fig. 355 gives an example taken from a machine with vertical axis, collecting 600 amperes at each brush set.

Another device for securing long commutator segments from bending up under the combined effect of temperature and centrifugal force, is to shrink over them around the middle an insulated steel ring. An example is given in the Thury generator, Fig. 453, p. 716. This plan is used for the commutators of dynamos driven by Parsons' steam turbines, see Fig. 483, p. 759. A form of commutator suitable for very high voltage is seen in Brown's machine, Fig. 480, p. 755.

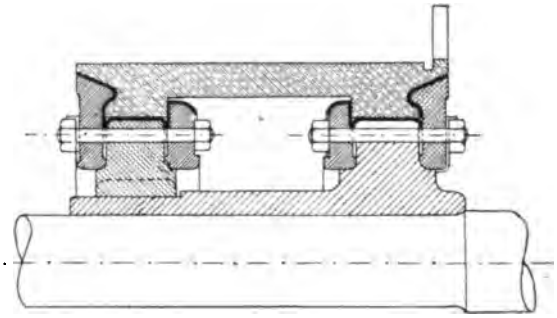


FIG. 354.—COMMUTATOR FOR LARGE CURRENTS (OERLIKON CO.).

Plate XXIII. shows the very compact and substantial construction adopted in the marine generator of Ganz and Co.

Occasionally, commutators are made of discoidal instead of cylindrical form, with the brushes resting against an end-face; but such end-face commutators are seldom seen except in little motors.

In building commutators it is usual to assemble the bars to the proper number, with the interposed pieces of mica, clamping them temporarily around the outside with a strong iron clamp, or forcing them into an external steel ring by hydraulic pressure. Hydraulic presses of special form for assembling commutators are made[1] by the West Hydraulic

---

[1] See illustrated article in *Engineering*, July 18, 1902.

Engineering Co., of Bradford. They are then put into the lathe and the interior cylindrical surface is bored out. Then the ends are turned up, with the annular hollows to receive the clamping-pieces. The whole is then mounted, with proper insulation, upon the sleeve, and the end clamping-pieces are screwed up. It is then heated in a stove, and the end clamping-pieces are further tightened up. Lastly the temporary external clamps or rings are removed and the external surface is turned up true. The commutators of large generators, which cannot conveniently be either hydraulically assembled or stoved, by reason of their size, are, after being assembled, heated by placing under them a ring of Bunsen burners at a distance of about a foot apart from one another. Then, when hot, the clamping-rings are tightened up with screws so as to squeeze out as much as possible of the shellac in the micanite. The sleeve should be properly keyed or otherwise secured to the shaft, or to the armature spider, that there may be no slip between it and the armature to which it is afterwards connected.

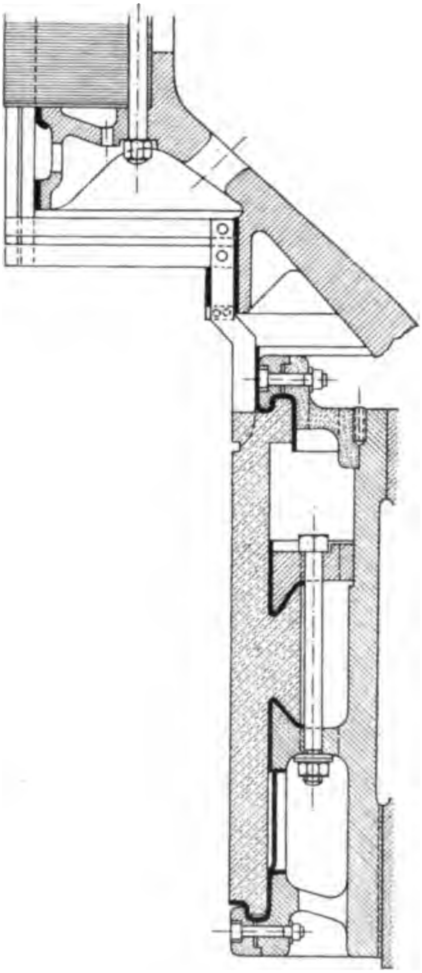


FIG. 355.—COMMUTATOR WITH MIDDLE SUPPORT TO SEGMENTS (OERLIKON CO.).

Commutator Risers.—Connexion is made with the armature conductors by means of radial strips or wires, sometimes called *risers*, which are inserted into a cut sawn in the corner of each bar, and firmly held there. A good mode is to rivet the strip connectors into the corners of the bars before they are assembled, each riveted joint being also sweated in with solder. Fig. 356 shows a simple mode of doing this; while Fig. 357 shows commutator bars formed with a lug to receive the rivet *r*. In this example the nick *h* is to prevent the brushes from being set too near to the radial strips.

It is important that these risers or radial connectors should be properly attached, since they are subjected to considerable mechanical forces. Twice in each revolution each such strip carries a strong current; and, owing to the existence of a stray magnetic field, may consequently be racked toward one side. Before this was understood it gave rise to frequent accidents. When copper brushes were universal there was supposed to be an advantage in designing these risers so that they offered resistance to the current, in order to improve the sparkless collection. Some makers use rheostene, others German-silver, and as in such cases the heating renders them liable to expansion and subsequent contraction, they are sometimes made of a wavy form, as Fig. 360*e*.

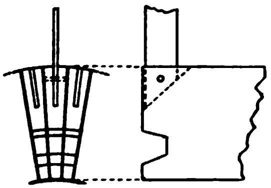


FIG. 356.—ATTACHMENT OF RISER TO SEGMENT.

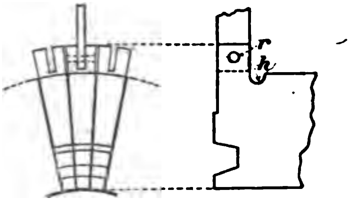


FIG. 357.—ATTACHMENT OF RISER TO SEGMENT.

For small machines another plan is to provide the segments with a lug, into which two holes are drilled as in Fig. 358, to receive the wires from the beginning and end of two successive sections of the winding; or the two wires are laid in a saw-cut and sweated in. German manufacturers often use screws for attaching the wires ; but English makers avoid them.

Attachment to the Armature Winding.—The risers are attached to the winding in several different ways. In cases of drums with evolute winding there is frequently no need of risers, inner ends of the evolutes being sweated into nicks in the ends of the segments, as in Fig. 310 and Plate XV. In larger examples, as in Plate XVII., short risers of strip copper are inserted. In cases of barrel-winding, risers are needed unless (as in Fig. 439) the commutator is very large. The risers are usually individually attached to the commutator before the latter is mounted on the shaft, and the connexions between armature and commutator are as the last operation.

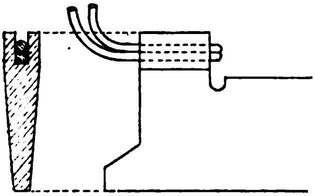


FIG. 358.—ATTACHMENT OF RISER.

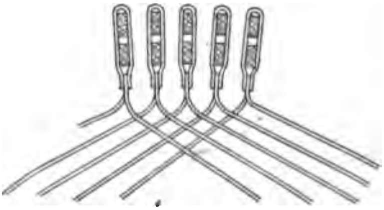


FIG. 359.—DOUBLE RISERS FOR EQUALIZING.

The attachment of the riser to the winding is often carried out, as shown in Fig. 360*a*, by sweating over the two projecting ends of the armature bars the recurved end of the slip that serves as riser. Another method used by Ganz and Co. is shown in Fig. 360*f*. Another method, due to Brown, consists in employing a curved riser which fits in under the projecting ends of the armature bars, as in Fig. 361. The three ends are individually tinned. They are then bound together by binding tightly around them a tinned copper wire. Lastly, when all have been so bound, the armature is suspended vertically and these connexions lowered into an annular pot of melted solder.

An unusual form of segment is depicted in Fig. 362, having a second lug projecting backward behind the riser

This is for the purpose of attaching the commutator to equalizing rings situated against the end of the core-body (see p. 412.

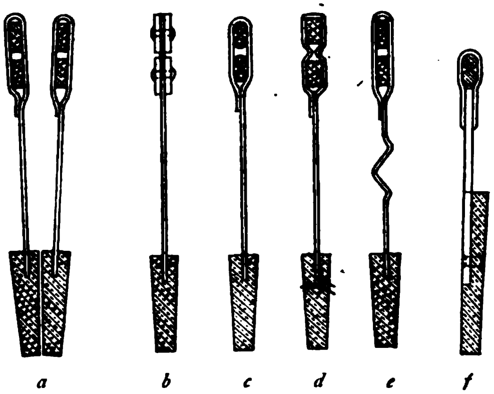


FIG. 360.—MODES OF ATTACHING THE RISERS TO THE ARMATURE CONDUCTORS.

Brushes.—Brushes may be classified into those made of metal, and those of carbon. The kind of metal brush most frequently used for receiving the currents from the commutator, consists of woven copper wire gauze folded on itself and compressed as shown in Fig. 363, *e*. It was introduced about 1884 by Mr. A. P. Trotter. In order to prevent fraying at the edge it is usual to fold the gauze obliquely, as in Fig. 363, *f*. Sometimes the core of this gauze is made of exceedingly fine copper wires either straight or in soft plaited strands. The

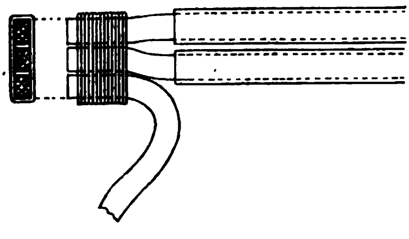


FIG. 361.—BROWN'S MODE OF ATTACHMENT.

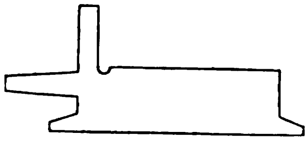


FIG. 362. — SEGMENT WITH EXTRA LUG FOR EQUALIZING CONNEXION.

earliest sort of brush used consisted of a quantity of straight copper wires laid side by side, soldered together at one end, and held in a suitable clamp. Two layers of wires were often thus united in a single brush, as shown in Fig. 363, *a*. The object of all these devices was to secure a contact at a large number of points.

Brushes made of broad strips of springy copper, slit for a short distance so as to touch at several points (Fig. 363, *b*), are used in the Brush and Thomson-Houston arc-light dynamos, and in rectifiers. This kind of brush is usually set tangentially to the surface of the commutator, not sloping to it at an angle as is the case with the thicker kinds of brushes.

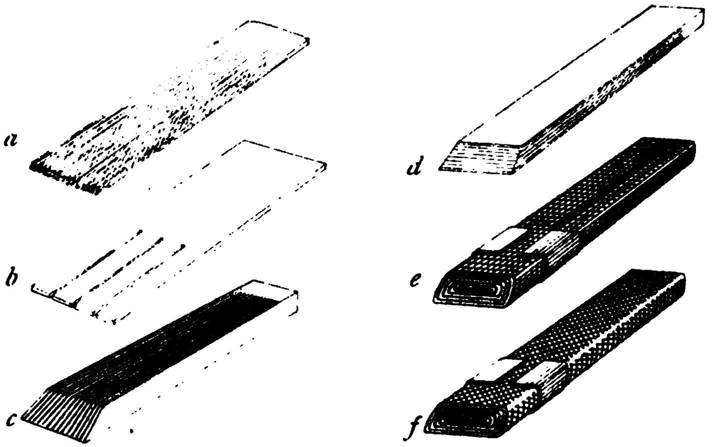


FIG. 363.—DIFFERENT KINDS OF COPPER BRUSHES.

Edison has used as brushes a number of copper strips placed edgeways to the collector, and soldered flat against one another at the end furthest from the collector, Fig. 363, *c*. In some machines, a compound brush made up alternately of layers of wire, like Fig. 363, *a*, and slit strips of copper, like Fig. 363, *c*, has been adopted.

Other makers have used a number of very thin copper strips laid over one another as in Fig. 363, *d*, held together in a suitable clamp. The best are those of Boudreaux.

Rotating brushes in the form of metal rollers or disks have been repeatedly tried, but are not successful.

Carbon Brushes.—It was suggested[1] by Professor G. Forbes to replace the brush by a slab of fine-grained and good conducting carbon. They have become practically universal for constant-potential machines, particularly for the generators and motors used in traction, in which the current to be collected is liable to frequent variations of amount, and where, therefore, the brush-holders and rocker must be kept in one constant position. It is not too much to say that without the use of carbon brushes it would be impossible to fix the position of the brush-holders and yet have sparkless performance at all loads. It is usual to provide a contact surface of about 1 square inch for each 40 amperes; but a really good conducting carbon will carry double this. At low surface speeds they wear the commutator less than copper brushes: but they are more liable to heat, and necessitate commutators of greater length. There are several qualities of carbon in use. For hard ordinary carbons a current-density, at the face, of 40 amperes per square inch is usual (see p. 240). For soft carbons, 60 to 70 are permissible; and with the special electro-graphitic carbon of brand "X," introduced by the company *Le Carbone*, 100 amperes per square inch are possible. Very soft carbons leave a layer of graphitic matter on the commutator, and at high voltages this may lead to sparking between neighbouring segments. Such carbons should only be used in low-voltage machines. Natural graphite behaves like soft carbon, but is more prone to cut the commutator. Carbon brushes are usually covered at their upper part with a coating of electro-deposited copper, to ensure good contact with the holder. This copper skin should be removed at the parts near the contact-face.

Number and Size of Brushes.—It is usual for all but the very smallest machines to place at least two brushes side by side (as in Fig. 14*a*, p. 29), instead of one broad brush. This allows of either brush being removed for trimming and replaced while the machine is running. It also tends to equalize the wear of the commutator, each brush being separately pressed against the surface; and the gap between two brushes can be covered by a brush at the other side. No rule can be given for the number or breadth of brushes that will apply to all cases. Nor is it easy to give a general rule for the thickness of brushes. A thickness that will bridge the film of insulation between bar and bar is not sufficient, for each section of the winding requires to be short-circuited for a certain brief time, in order that the current in it may be reversed. The minimum thickness of metal brush (or breadth of its oblique end) seems to be about 1½ times the thickness of the commutator bar. Carbon brushes are more usually made broad enough to span over 2½ bars. For armatures with duplex and triplex windings (p. 367) broader brushes must necessarily be used. There is no objection to a greater thickness in those dynamos that have a large neutral zone about the neutral point. But when a brush of great thickness is used another effect arises, namely, a waste in heating owing to the difference of potential between the parts of the commutator respectively in contact with the advance edge and hinder edge of the brush. To reduce this effect it has been proposed to use two thin brushes, one in front of the other, instead of a single thick one, with a certain amount of resistance between them.

---

[1] Specification of Patent 1288 of 1885.

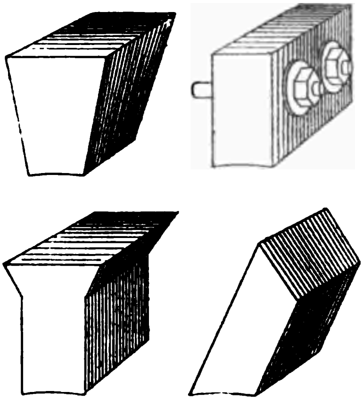


FIG. 364.—VARIOUS CARBON BRUSHES.

Mordey has suggested[1] a special form of brush, consisting of a number of thin laminæ (Fig. 365) slightly insulated from one another at the face, but united above, so as to introduce a small resistance between those that touch on different segments. Rothert has shown[2] that there is some advantage in having brushes that possess a higher specific resistance toward the toe. A similar advantage may be gained by the plan introduced by Crompton of employing a mixed brush of copper and carbon, the carbon tip being set beyond the copper brush so as to come into operation at the close of the commutation. In large machines, where a number of brushes are fixed side by side on one brush-rod, constituting a "set" of brushes, there is some advantage in using holders of unequal lengths, so that the positions of the brushes are staggered. The brush which projects furthest should in that case be made of a carbon of higher resistance.

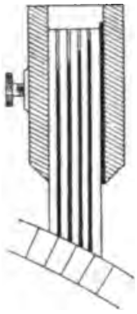


FIG. 365.—MORDEY'S LAMINATED BRUSH.

Setting of Brushes.—The angle at which brushes are set to bear upon the commutator varies with the construction. As a rule the brush is set sloping at an angle, the tip of the brush being raked in the direction of the rotation, so that it may not trip on the edges of the commutator-bars. In Fig. 366, *a*, is shown such a brush, set tangentially, as in arc-light machines. In Fig. 366, *b*, is a thick brush with bevelled end set at about 45°, as in most constant-voltage dynamos. Fig. 366, *c*, shows a form of brush for use in

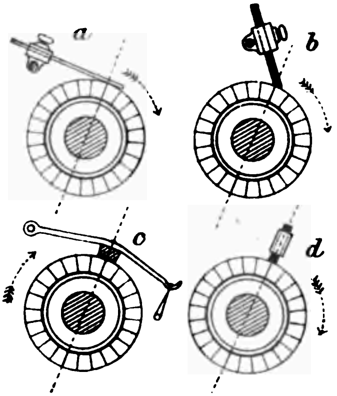


FIG. 366.—SETTING OF BRUSHES.

---

[1] *Journ. Inst. Elec. Engineers*, xxvi. 562, 1897.

[2] *Elektrotechnische Zeitschrift*, Oct. 1902.

motors, permitting of reversal of direction. Blocks of copper or gun-metal are attached to levers furnished with rubber bands to afford contact-pressure. In Fig. 366, *d*, is shown a carbon brush also adapted for use in reversing motors; the brush, a rectangular block of carbon, being pressed radially through a metal slide against the commutator.

In many cases where carbon brushes are used they are set to rake in a direction opposite to the rotation, so that the end-pressure may be greater when running. Fig. 367 illustrates a carbon brush-holder for use in mining motors.

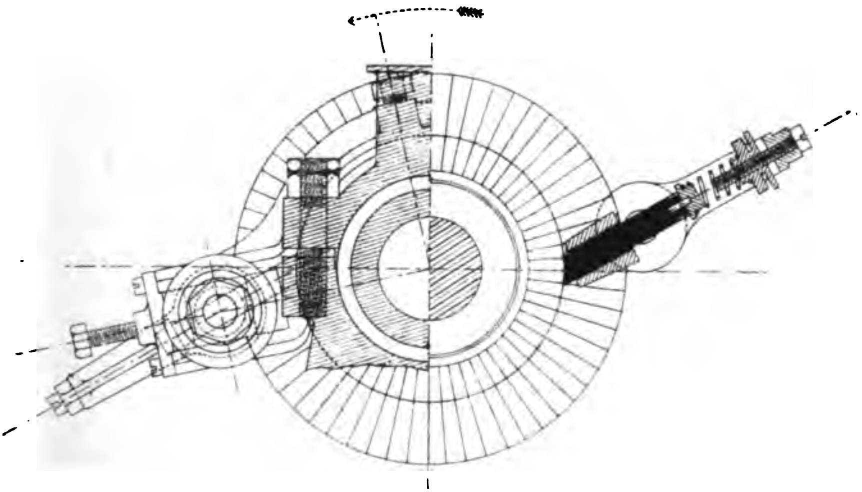


FIG. 367.—CARBON BRUSH-HOLDER (SNELL).

Brush-holders and Rockers.—The mechanism for holding the brushes must fulfil the following conditions:—

1. The brushes must be held firmly, and joined with a good metallic contact to their circuit.

2. Brush-holders must permit brushes to be withdrawn or fed forward as required.

3. Brushes must be held to make contact at proper angle to the surface of the commutator.

4. Brushes must bear with proper pressure upon the commutator; if too light, they will jump and spark; if too heavy, they will cut the commutator into ruts.

5. They must not have too great an inertia, as they have to rise and fall gently if the commutator be in the least untrue.

6. Brush-holders must permit brushes to be raised from contact.

7. For small machines they must also permit, by a proper mechanical catch, of the brushes being held raised out of contact.

8. Insulated handles should be provided for all dynamos working above 100 volts, so that the brushes may be raised and adjusted without risk of shocks.

9. The insulation of the brush, or of brush and brush-holder together, must be very thorough.

10. The rocker and brush-holder rods must be firm and steady, so that the vibration of the machine when running shall not cause chattering of the brushes.

An example of metal brushes, designed by Mr. Mountain for the "Tyne" dynamo, is given in Fig. 368, which also shows the construction of the commutator and the rocker. The rocker R consists of an iron ring in two parts, which is clamped together by bolts upon a raised rim on the bearing. To this rocker are attached a handle H for shifting it so as to bring the brushes to the neutral point, and a couple of projecting lugs L (one only shown) to carry the brush-holder rods M. The latter are mechanically secured to the rocker lugs by screw nuts which hold them tightly ; but they are electrically kept from making contact with the rocker by the interposition of an insulating bush and washers of ebonite. Upon the rods M are placed the brush-holders A which can turn hinge-wise upon them. Between the hinges of A is fixed, by a screw F, a middle piece D with a projecting tail. The brush B passes through a slot in A, being clamped by a screw C. The current is brought to the brush-holders by flexible conductors, which are soldered into sockets provided for the purpose. The brush is pressed forward by a compressed spiral spring, the force of which can be regulated by a screw through the projecting tail of D ; whilst it can be held off by means of the catch K, which can be pulled back and slipped into a cleft on the end of D. In Fig. 353, p. 491, which depicts the similar mechanism of the Gülcher dynamo, one of the hold-off catches is caught in the cleft.

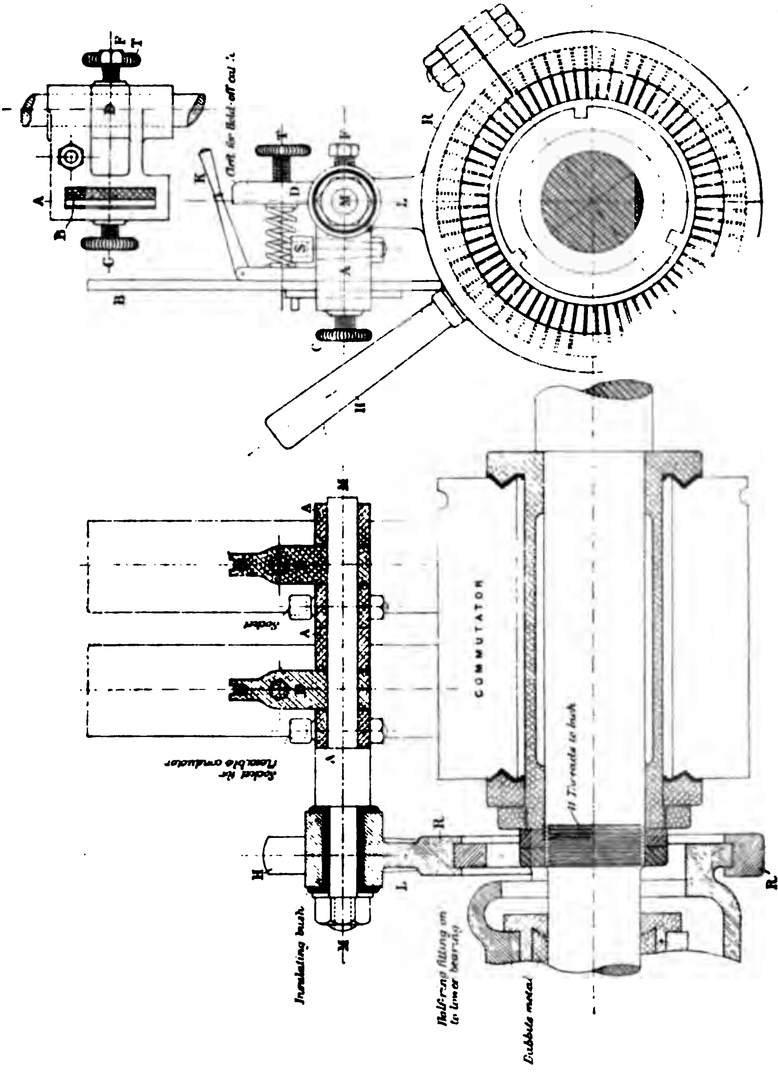


FIG. 368.—ROCKER AND BRUSH-HOLDERS OF "TYNE" DYNAMO.

The rocker and brush-holders of the Kapp 2-pole dynamo are shown in detail in Plate III. Here the mode for insulating is the same, but the current is led into a thick washer G; the contact-pressure is produced by an extended spiral spring stretched between a lug on the holder A and the fixed tail D ; and the hold-off catch K is constituted by a straight spring which engages in a notch on the corner of A and is released by pressing up the piece Q, which is made of hard fibre. P is a pointer for setting the brushes to the right position in the holder.

Various inventors have tried to simplify the construction ; amongst them, Parsons has proposed to substitute weights for springs to give the requisite pressure.

A very simple and effective form of metal brush-holder, introduced by Siemens and Halske, is used largely in Germany. In this form, Fig. 369, the clamp which holds the brush is set on the end of a curved support made of several thicknesses of springy sheet brass. This is simply clamped to the holder-rod by a clamp screw which admits of the holder being shifted along the rod, or of being turned to give greater or less pressure. The same tool is used for either of the required adjustments.

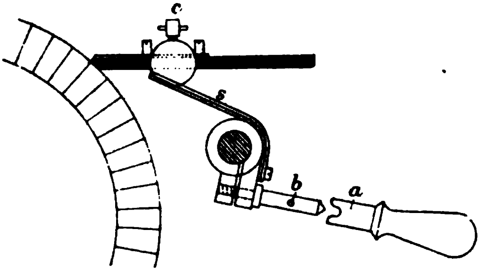


FIG. 369.—SIEMENS AND HALSKE'S BRUSH-HOLDERS.

Holders for Carbon Brushes.—The current forms may be classified under three types :—

1. *Hinged Structures.*
2. *Parallel Spring-holders.*
3. *Reaction-holders.*

Fig. 370 depicts some of the forms used by Messrs. Siemens and Halske. Fig. 370 *a* is a hinged form in which the carbon is clamped in a light frame that can turn around the cylindrical brush-pillar, and which is pulled down by a spring attached to an inner piece fixed by a screw to the brush-pillar. Fig. 370 *d* is a kindred form having a coiled spring within, and a flexible copper ribbon above it to carry the current to the carbon. Fig. 370 *b* has a parallel spring-holder. Fig. 370 *c* is another view of Fig. 369.

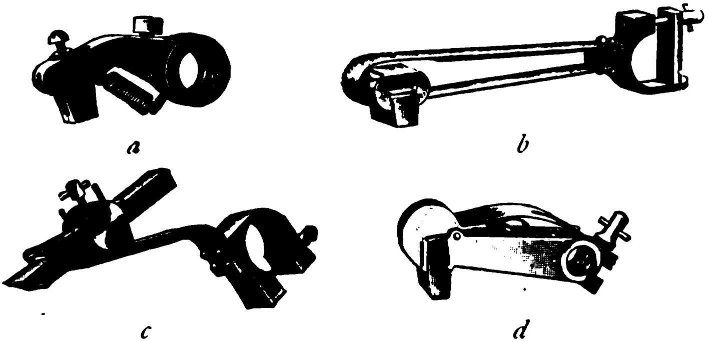


FIG. 370.—BRUSH-HOLDERS (SIEMENS AND HALSKE).

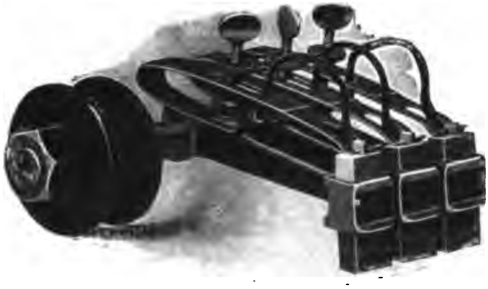


FIG. 371.—BRUSH-HOLDER (BRITISH THOMSON-HOUSTON).

Fig. 371 depicts an American type used by the British Thomson-Houston Co. It shows how the brush-pillar is mounted upon a strong insulating bush which is itself borne upon the rocker. The brush-pillar carries a set of three carbon brushes. Each brush is of rectangular form and slides through a holder that is rigidly screwed to the brush-pillar. A spring bears on the top of each "brush", and a stranded copper "flexible" conveys the current. These flexibles are inserted into a hole drilled in the carbon and filled in with solder or lead. A somewhat similar but improved holder, of lighter pattern, is depicted in Fig. 372, having parallel springs.

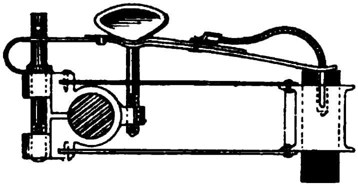


FIG. 372.—PARALLEL SPRING BRUSH-HOLDER.

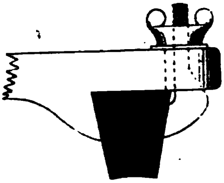


FIG. 373.—BRUSH CLAMP.

Another hinged form, largely used on the Continent, and due to Boudreaux, is shown in Fig. 374. In this example the carbon brush is held to the hinged lever by a hinged jaw, and good conduction of current to the carbon is ensured by a flexible ribbon of copper seen below the lever.

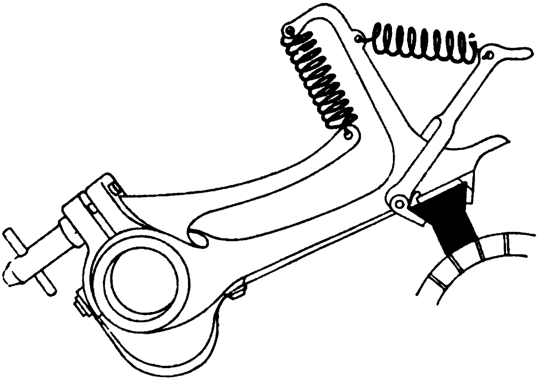


FIG. 374.—BOUDREAUX BRUSH-HOLDER.

Another mode of securing a good conducting contact is represented in the clamping device shown in Fig 373.

To the hinged type belongs the brush-holder (Fig. 375), designed by Mr. V. A. Fynn, to carry 25 to 30 amperes. It consists of two aluminium castings; one clamped firmly to the rocker-bar by means of the screw; the other, of triangular form, carrying the carbon block, being loose on the rocker-bar.

A cylindrical spring connects the clamp to the top of the triangle, and presses the carbon brush on the commutator.

The current is conveyed from the brush by six copper strips sweated to the brush-holder and clamp. The design is noticeable for the way in which the parts of the brush-holder are kept as far away from the commutator as possible.

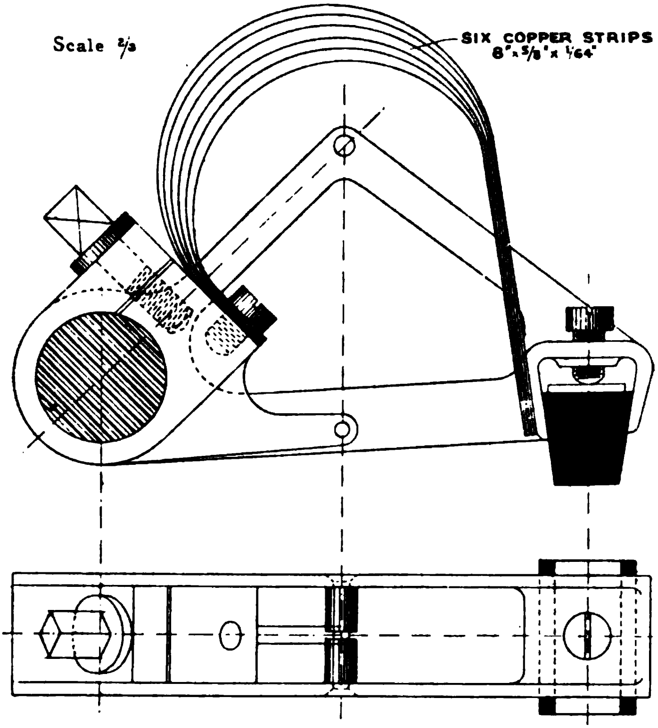


FIG. 375.—FYNN'S BRUSH-HOLDER.

A brush-holder of the reaction type, due to Messrs. Armstrong, Mitchell and Co., is shown in Fig. 376. A lug riveted to the magnet-frame supports the insulated metal casting through which the rectangular carbon brushes slide. They

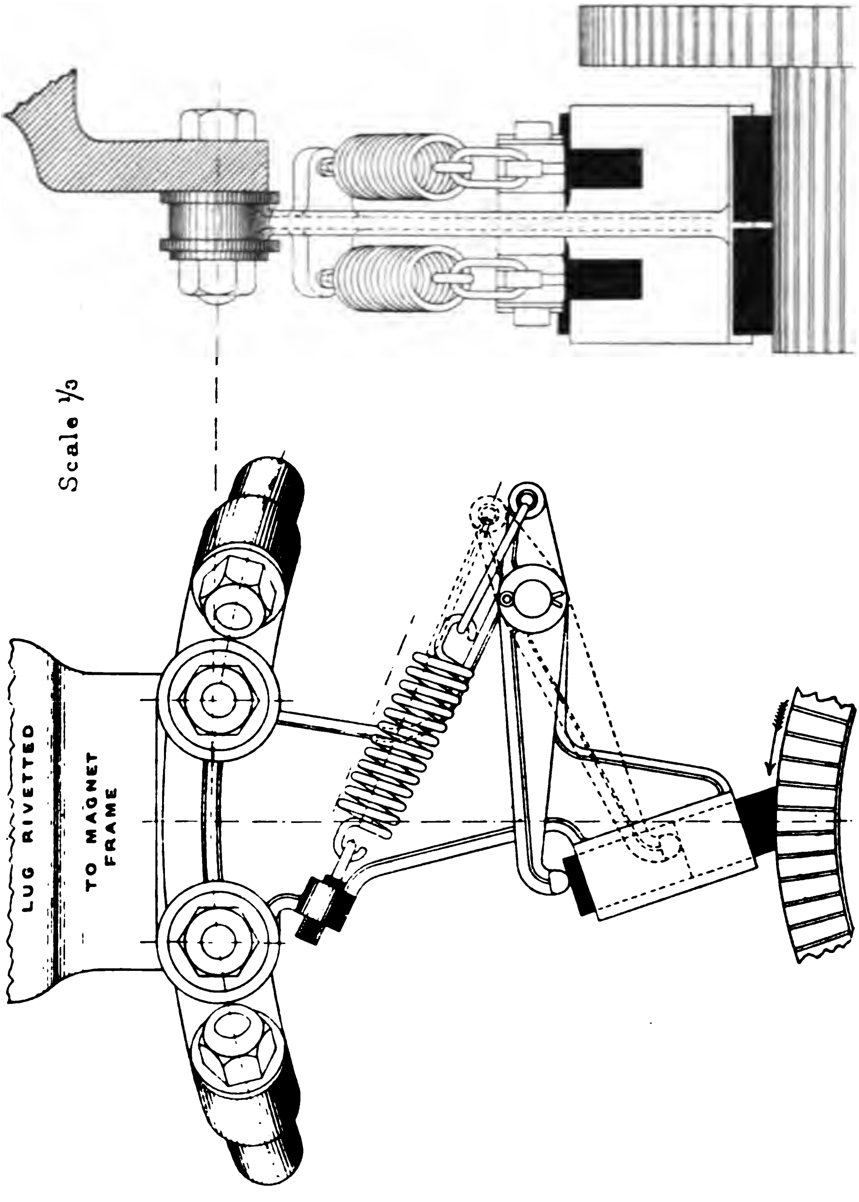


FIG. 376.—REACTION BRUSH-HOLDER (ARMSTRONG, MITCHELL AND CO.).

are pressed against the face of the commutator by a lever controlled by a spiral spring. The brushes rake against the direction of revolution of the commutator, so that the reaction of the frictional forces improves the contact.

Another form of reaction brush-holder, designed by the late Professor Short, is depicted in Fig. 377.

In this form the carbon brush C presses against the commutator K, and against the oblique face of a gun-metal block fixed by a set-screw *g* upon the brush pillar P. A pair of light levers L (one behind the other and joined by transverse pins) hinge about a second axis S; they press by small rollers on the carbon C, and are thrust forward by means of a coiled wire-spring *w*, one end of which is fastened through a hole in L, and the other, after making a few turns round the shaft S, is bent up and crooked so as to engage in a toothed piece T in some position that produces sufficient force.

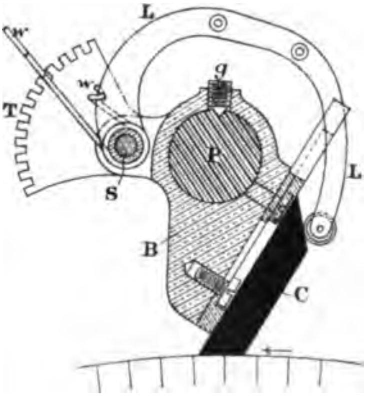


FIG. 377.—REACTION BRUSH-HOLDER (S. H. SHORT).

Rockers and Brush-Rods.—For bipolar and small multipolar machines the rocker is almost always constructed to clamp upon the bearing in the manner shown in Figs. 353 and 368. Enlarged drawings of rockers and brush gear may be seen in Plates IV., VII., and XXII.

For large multipolar generators and motors, the rods on which the brushes are held are fixed at equidistant points around a cast-iron *rocker-ring* which is itself supported on four or more brackets projecting from the magnet-yoke. This construction is seen in Figs. 378, 379, 380 and 434, and in Plates XII. and XX.

In these cases a worm-gear and hand-wheel are usually supplied for moving the rocker-ring so as to adjust the brushes to make contact with the proper amount of lead. The several sets of brushes are connected together in two groups, positive and negative. This is sometimes effected by the use of flexible cables, as in the Kolben machine, Plate XVI., but more often by the adoption in the design of the ring of two insulated copper conducting rings (sometimes called "bus-rings"), one behind the rocker-ring the other in front of it. The positive brush rods are joined to one of these copper rings, the negative rods to the other. This construction is shown in Figs. 378 and 379.

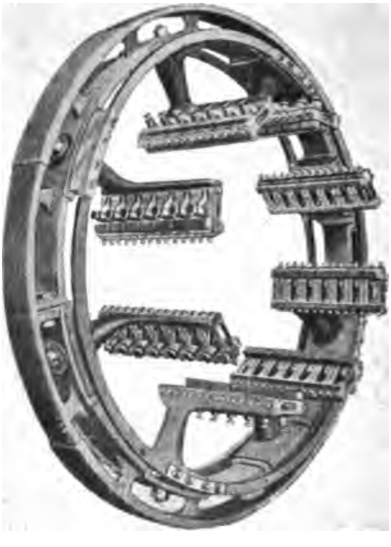


FIG. 378.—ROCKER-RING AND BRUSH GEAR (CROCKER-WHEELER CO.).

Analogous constructions may be noted in Figs. 419, 432, and 434, and in Plate XIX. Fig. 380 shows the form of rocker-ring used by the Messrs. Dick, Kerr and Co. It is designed in two separate halves of hollow section, within

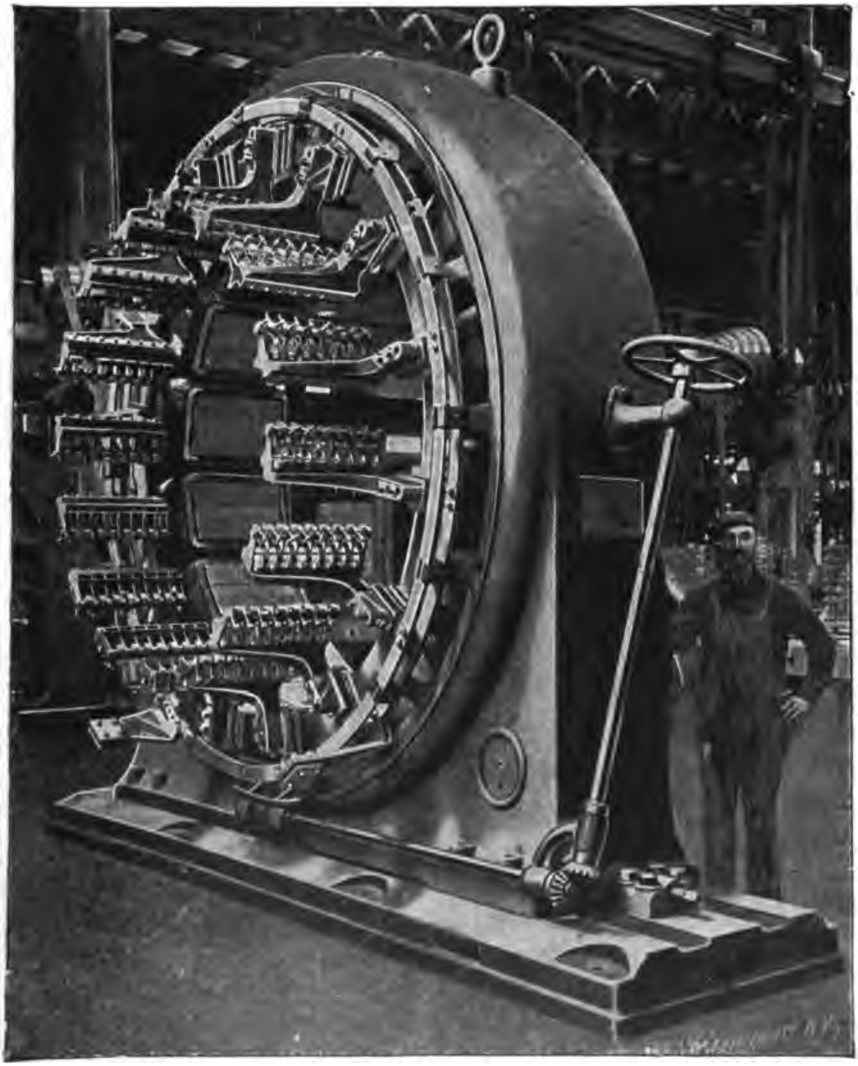


FIG. 379.—FIELD-MAGNETS AND BRUSH-HOLDERS OF WESTINGHOUSE 850 KILOWATT ELECTROLYTIC GENERATOR.

which the conducting rings, positive and negative, are protected.

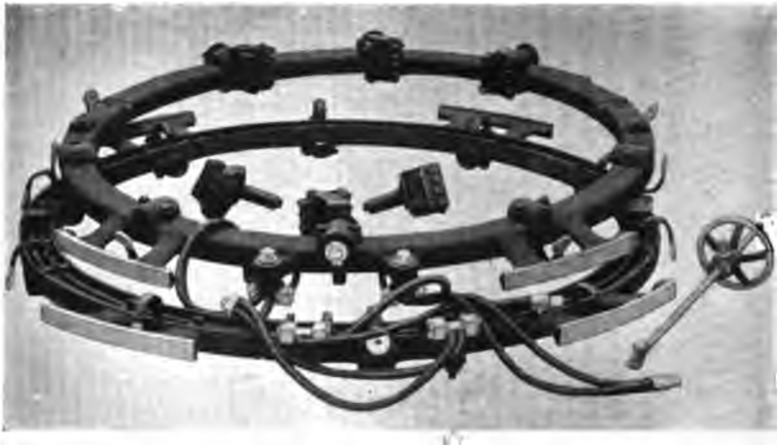


FIG. 380.—ROCKER-RING AND BRUSH GEAR (DICK, KERR AND CO.)

It will be observed that in the Westinghouse gear there is a radial adjustment for each brush-row. An excellent example of this adjustment was seen in a dynamo by W. Smit of Haarlem in the Paris Exhibition of 1900.

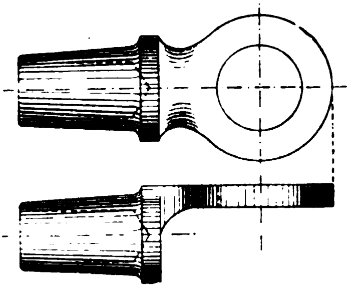


FIG. 381.—SWEATING LUG.

A third plan is to support the rocker-ring on an independent support above the commutator. This construction is depicted in Fig. 452, p. 715.

Sweating Lugs and Terminal Thimbles.—Amongst the details of brush-gear are the contrivances for bringing the current to and from the brush-pillars or rocker-rings. This is usually accomplished by the use of large flexible connexions made of stranded copper wire braided externally. Examples are seen in Plates XV., XVI., XX., and XXV. It is necessary that all such flexible leads should make good contact at their ends to suitable solid metallic pieces. On the rocker there are usually provided sweating lugs (Fig. 381), of copper or brass, into which the ends of the flexible cable are sweated with solder. Their other ends are sweated into suitable thimbles or sockets on the terminal board.

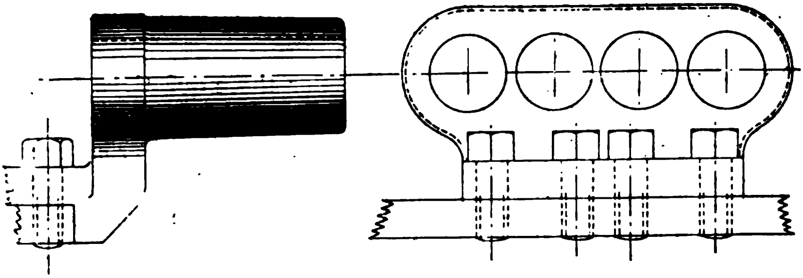


FIG. 382.—SWEATING THIMBLES ON TERMINAL BOARDS.

Fig. 382 depicts a set of thimbles suitable for a terminal board.

CHAPTER XVII.

ESTIMATION OF LOSSES, HEATING, AND PRESSURE-DROP.

IN this chapter we propose to consider these questions from the designer's point of view, as they are leading features of any design and require to be accurately predetermined from the drawings. On account of the diminishing importance of bipolar machines and of those with smooth core armatures, we shall consider, both in this chapter and the next (which deals with the design of continuous-current machines), the case more particularly of multipolar machines with slotted armatures.

The losses occurring in any dynamo or motor come under six heads, as follows:—

A. *Copper Losses.*—These consist of the sum of the C^2R losses in armature and series coils (if any) and increase with the load, but are independent of the speed.

B. *Iron Losses.*—These are made up of the eddy-current and hysteresis losses produced in the armature core-plates owing to the changes of flux-density to which they are subjected in each revolution. They vary slightly with the load, and are always variable with the speed. There are also certain losses in the case of machines with toothed armatures due to the production of eddy-currents in the pole-pieces.

C. *Excitation Losses*, that is, the watts expended in heat, in driving the magnetizing current around the magnetizing coils; which losses must be debited against the dynamo, as they lessen the efficiency.

D. *Commutator Losses.*—These consist of—

(1) C^2R loss on account of contact resistance.
(2) Brush friction loss.

(3) Losses through sparking, and through eddy-currents in the commutator bars.

Of these, Nos. (1) and (2) are as a rule the only ones necessary to consider. There are also local circuits in the brushes producing a small loss of energy..

E. *Friction and Windage Losses.*—The former is the loss due to friction of bearings, which depends only upon the load. The latter is the loss occasioned by the armature churning the air. It is independent of the load but varying with speed.

F. *Secondary Copper Losses.*—We will consider these separately.

(A.) *Copper Losses.*

Let w_c represent the total copper loss of the machine.
" r_a " (hot) resistance of the armature.
" r_m " " " " series coils.
" C_a " full-load armature current.
" l " total length of armature conductor *in feet*, including end connectors.
" s " section of the armature conductor *in sq. inches.*

Then we have for the total resistance of the conductors on the armature, considered as all in series irrespective of their grouping,

$$r = \left[0{\cdot}000008 \times \left\{ 1 + 0{\cdot}004\,(t - 15) \right\} \frac{l}{s} \right]$$

at a temperature of t° C. This formula becomes at temperatures of about 60° C. (compare p. 157),

$$r = \frac{9{\cdot}5 \times l}{10^6 \times s}.$$

The actual resistance proper of the armature r depends on the form of winding employed, and the number of circuits in parallel from brush to brush, the rules for which are given on p. 376. For all bipolar machines and simple series-connected multipolar armatures, with two circuits only, the rule becomes $r_a = r \div 4.$

For simple multipolar parallel-connected armatures running in fields of p poles, we have

$$r_a = r \div p^2,$$

because there are as many circuits as poles.

Then the copper loss of the machine is

$$w_c = (C_a^2 \times r_a) + (C_m^2 \times r_m).$$

A convenient aid in reckoning the copper losses is afforded by Table XI., p. 181, which gives the relation between the ampere-density and the energy loss in copper.

(B.) *Iron Losses.*—For the calculation of the hysteresis loss, we can either make use of the formula given on p. 100, or, better still, refer to a curve obtained by test upon the actual iron. Such a curve is shown in Fig. 54, the ordinates giving directly the watts lost per pound of iron at the different flux-densities given by the abscissæ, and at 30 periods per second. To find then the hysteresis loss in a slotted armature, for instance, we proceed as follows. First, calculate the number of complete magnetic reversals, thus

$$f = \frac{1}{2} \frac{\text{revs. per min.}}{60} \times p;$$

where f is the frequency, p the number of field-poles. Next calculate the actual flux-densities B_4 and B_5 in teeth and armature core respectively. A reference to the upper curve of Fig. 54 will give the corresponding number of watts lost per pound of iron at these flux-densities. Multiplying the two numbers so obtained by the total weight of the iron in teeth and core, and adding the two results we obtain the hysteresis loss in the armature at $f = 30$ periods per second. If the frequency of reversal is either higher or lower than this, the hysteresis loss will be proportionately greater or less. Instead of computing these losses from the weight of the iron we may compute them from the volume (cubic inches) by the curves given in Fig. 55 on p. 103, or estimate it from Table VII., p. 102.

The eddy-current losses are proportional to the square of the flux-density, to the square of the frequency, and to the square of the thickness of the armature plate. They may be calculated from the formula (see p. 104),

$$\text{Watts lost per cub. inch} = (40{\cdot}64 \times t^2 \times f^2 \times B^2)\, 10^{-12},$$

where t represents the thickness of plate in inches. As, however, this formula takes no account of the short-circuiting of individual plates caused by the machining of the armature, the results given by the formula will always be found to be too small. The error is partly compensated for by the fact that the formula is based upon the specific resistance of iron at 0° C., and as the armature will always be fairly hot, the increase of resistance will diminish the eddy-current loss. But a reference to the lower curve of Fig. 54, p. 101, will usually give good results, and it is easier to apply as it gives directly the eddy-current loss per pound at different flux-densities for the standard thickness of English armature plate, viz. 25 mils, and for 30 periods per second. It contains a correction-factor to cover the loss due to the after-tooling of the core, but should the frequency (or thickness of plate) be greater or less than the one for which the curve was plotted, the final result must be raised or lowered in proportion to the square of the frequency or plate-thickness. Table VIII. on p. 104 and the curves of Fig. 56 on p. 105 are also useful.

We have assumed above that the volume of active iron is the same as the actual volume of iron in the armature. This is of course not strictly true, as some of the teeth and perhaps a small portion of the core may be missed by the flux going from pole to pole. The error is, however, negligible, and is on the right side. It tends to correct for the eddy-current loss in the pole-faces, which is impossible to calculate. The iron loss of the armature is hence

$$w_i = w_e + w_h,$$

where w_e and w_h are the eddy-current and hysteresis losses respectively, evaluated separately as above.

(C.) *Excitation Losses.*—If r_{sh} is the resistance (hot) of the shunt winding, calculated by means of one of the resistance formulæ already given, and V the electromotive-force at its terminals at full load, we have $\left(\frac{V}{r_{sh}} \times V\right) = \frac{V^2}{r_{sh}}$ as the watts actually used in excitation. To these must be added the loss in the shunt regulating resistance, if any, giving a total loss of w_x watts at full load. The watts required for excitation purposes by shunt machines vary in practice from one to ten per cent. of the output, according to the size of machine. As a guide to the designer in this direction, the table below may be useful, as giving maximum permissible loss.

Output of machine in kilowatts.	Excitation loss in per cent. of full-load output.
5	6
10	5
20	4
30	3·5
50	3
100	2·75
200	2·5
300	2·25
500	2·0
1000	1·75
2000	1·5

(D.) *Commutator Losses.*—The contact resistance between commutator and brushes depends mainly upon (1) the material of the brush; (2) the bearing pressure; (3) the peripheral speed of the commutator; and (4) the current-density in the brush. Other causes, such as the condition of commutator and brushes, weight and spring of the brush-holders, etc., will also influence the contact resistance to a greater or less extent. The voltage-drop at the commutator and the energy loss due to it may be estimated by the methods explained in Chapter X., p. 242. As a quick approximate rule it may be remembered that with carbon brushes collecting current with a density of about 40 amperes per square inch at the face, and a pressure of about 1·5 lb. per square inch, the pressure drop will be from 1·6 to 2·0 volts on the machine (*i.e.* about 0·8 to 1·0 volt at the positive, and as much at the negative contacts; with copper brushes the drop is usually less than one-tenth of this amount). Hence multiplying the current output by 1·6 or 2 will give the number of watts lost.

Example.—In Brown's large electro-metallurgical machine, p. 609, the current output is 4000 amperes at full-load. If there is a drop of 2 volts, the commutator loss due to contact resistance will be:—

$$2 \times 4000 = 8000 \text{ watts.}$$

The loss arising through the friction of the brushes against the rotating commutator depends upon the bearing pressure of the brushes, the peripheral speed of the commutator, and the *coefficient of friction* between the two. If brushes and commutator are in good condition this latter may be taken as

For carbon brushes . . .	0·3
„ copper „ . . .	0·2

In order then to calculate the watts lost through brush friction, we simply multiply the total pressure on the commutator (in pounds) by the peripheral speed in feet per minute and by the friction coefficient, which gives the losses in foot-pounds per minute, and then reduce to watts by dividing by 33,000 and multiplying by 746. Or, since $\frac{746}{33000} = 0·0226$ the foot-pounds per minute may be brought to watts by multiplying by this figure, or by dividing by 44·2 which is its reciprocal.

Example.—Taking as example the same machine, if we assume the brush pressure as 1·55 lb. per square inch, and the friction coefficient as 0·3, since the peripheral speed of the commutator is 3350 feet per minute, we have as the friction loss

$$160 \times 1·55 \times 0·3 \times 3350 \times 746 \div 33{,}000 = 5650 \text{ watts.}$$

In estimating commutator-losses it must be borne carefully in mind that with brushes or commutator in bad condition the losses (both mechanical and electrical) will probably come out considerably greater than the above calculations indicate.

Commutator Heating.

Let w_b represent the total commutator loss, electrical and mechanical, in watts.
„ S_3 represent the heat radiating surface of commutator in square inches.
„ v represent the peripheral speed of the commutator in feet per minute.
„ θ_e represent the final temperature rise, in degrees Centigrade.

Then, according to tests made by Professor E. Arnold,

$$\theta = \frac{46{\cdot}5 \times w_b}{S_3 (1 + {\cdot}0005\, v)}.$$

According to Messrs. Parshall and Hobart, the rise of temperature of the commutator will seldom exceed 20° C. per watt per square inch of peripheral radiating surface at a peripheral speed of 2500 feet per minute; for ventilated commutators this figure may be considerably improved upon.

(E.) *Friction and Windage Losses.*—These are naturally very difficult, if not impossible, to calculate with any accuracy, and are usually estimated by the designer from previous experience of the same type of machine as a percentage of the full-load output. Direct-coupled machines will have smaller friction losses than belt or rope-driven machines, and low speed dynamos smaller mechanical losses than high-speed machines of the same output. For belt- or rope-driven machines running at the usual speeds found in practice, the mechanical losses may be taken as being from 3 to 1 per cent. for outputs of 10 to 300 kilowatts. For an approximate method of calculating the mechanical losses of dynamos, the reader should consult Fischer-Hinnen's *Continuous-Current Dynamos*, London, 1899.

Efficiency.—Having estimated the separate losses, it becomes a very simple matter to calculate the efficiency of the machine for the load at which the calculations were made. By the efficiency we mean simply the relation between the power actually delivered electrically at the terminals of the dynamo to the mains, and the power applied mechanically at the shaft to turn the armature, both qualities being for convenience expressed in watts, so that we may write the efficiency as

$$\frac{\text{Output watts}}{\text{Input watts}} = \eta.$$

There is little advantage in separating the efficiency into factors, "electrical efficiency," etc., as the above definition includes everything within the true use of the term. If W is the output in watts of the dynamo or motor, and Σw the sum of all its losses as estimated above, we have

$$\eta = \frac{W}{W + \Sigma w} \times 100$$

as the true or commercial efficiency expressed as a percentage. The efficiency will differ at different loads, since the watts lost constitute a different proportion at different outputs. The core-losses are nearly constant at all loads, and so is the loss of energy due to excitation by the shunt coils. The question what the efficiency will be at ½-load, or ¼-load, or at 1¼ load depends largely on the proportion of the various losses. At no-load there are hysteresis and eddy-currents in the iron core-body, excitation losses, and friction. As the load increases there is added the loss by heating in the copper of the armature, and in the series coils; and these losses increase with the square of the current. Consequently the efficiency, which at no-load is zero, goes up to a certain maximum, which, if the design is good, should be at the normal full-load; but it should be high also at half-load and even at one quarter-load.

The form of the efficiency curve is shown by a typical example in Fig. 383, which also shows the values of the separate losses at different loads. This set of curves relates to a particular 6-pole 200-kilowatt machine, supplied by the General Electric Company to the Central London Railway

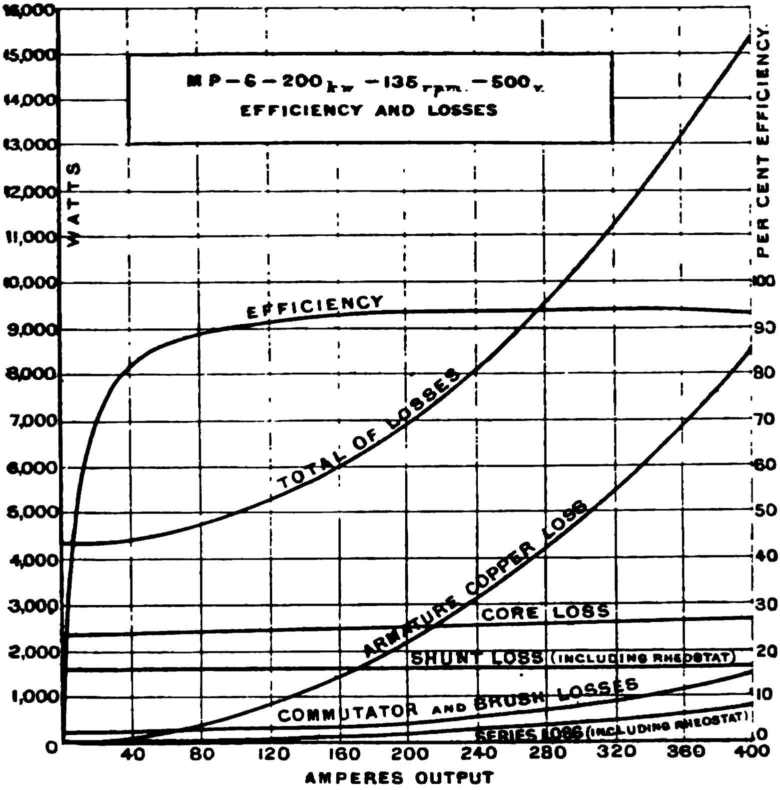


FIG. 383.

and described by Messrs. Parshall and Hobart.[1] Fig. 384 shows how the excitation in this same machine automatically increases with the load by the compounding action of the series coil.

(F.) *Secondary Copper Losses.*

In addition to the ordinary ohmic loss of power due to the resistance of the armature conductors, there are certain

[1] *Electric Generators*, p. 190.

obscure causes of loss that lower the measured efficiency of machines. One of these is the production of eddy-currents in pole-pieces, heating them and wasting some of the power applied to drive the armature. Another is the production of eddy-currents in the copper conductors themselves. Akin to this is the actual increase of resistance which occurs if for any reason the current in the conductor does not distribute itself equably in the cross-section, as explained on p. 444.

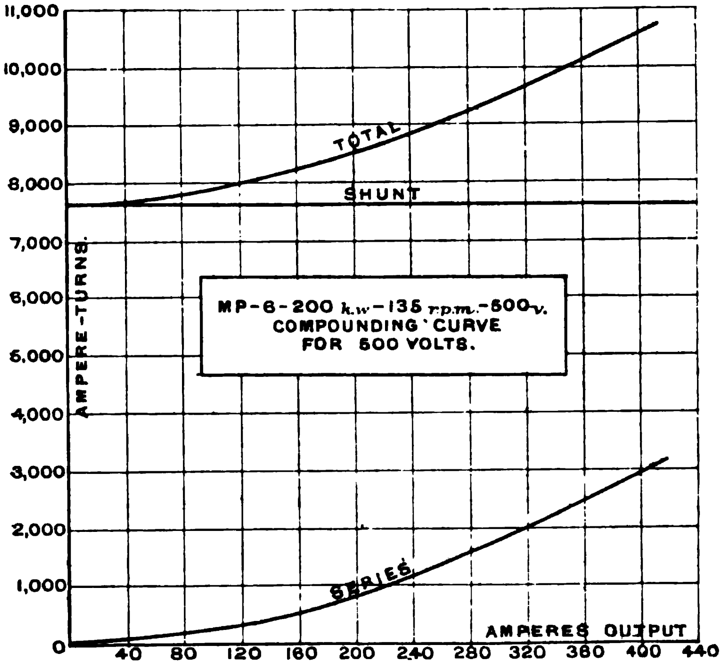


FIG. 384.

There are also eddy-current losses in the commutator owing to the presence of stray magnetic fields surrounding the brushes and brush-pillars. These latter losses are small compared with those previously mentioned. If the armature is not provided with equalizing connexions (p. 412) there will be additional heat losses as the load rises owing to the unequal distribution of current between the various circuits in the winding.

Calculation of the Pressure-Drop.—It was shown in Chapter VI. how to construct the saturation curve of a dynamo machine, that is, the curve connecting the ampere-turns upon the magnetic circuit and the useful flux produced by them in the air-gap. Let O C in Fig. 385 represent such a *saturation curve*, the ordinates representing the flux being cut by the conductors and the abscissæ the ampere-turns producing it. Now the fundamental equation for the induced electromotive-force (p. 282) tells us that

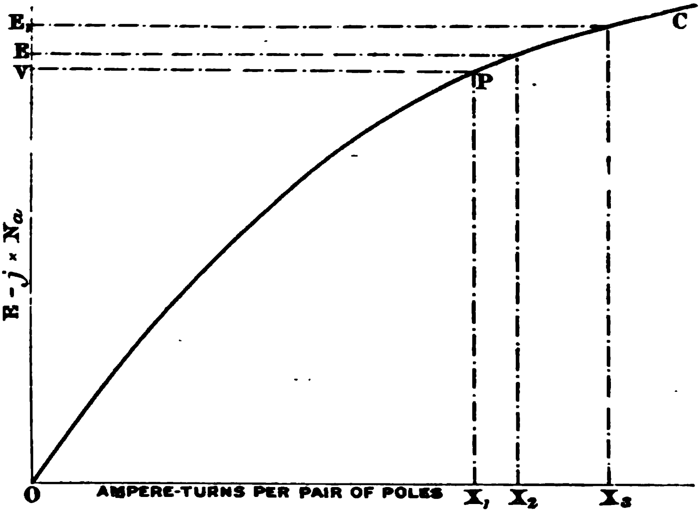


FIG. 385.—SATURATION CURVE OF DYNAMO.

$$E = \frac{p}{c} n Z N \div 10^8,$$

or that $E = N_a \times$ a constant depending upon the construction and operation of the machine, and which may be denoted by j. Consequently the ordinates of the curve represent the induced electromotive-force to a different scale, that is, $E = j\, N_a$, and we may therefore regard it as being the curve of induced electromotive-force of the machine for different excitations at constant speed—in other words, it is the "no-load characteristic" of the machine. Assuming then that Fig. 385 represents this curve for a particular machine, we can see from it what the pressure-drop at constant speed and excitation will be, and incidentally determine the amount of compounding that must be employed in order that constant pressure may be maintained at the terminals of the load. Let the ordinate O V represent this constant pressure. Evidently at no load an excitation of X_1 ampere-turns are required. Now at the full load of C_a amperes, there will be three causes tending to lower the pressure, namely the effects of (*a*) ohmic resistance of armature and series coils; (*b*) demagnetizing action of the armature; and (*c*) distortion of the armature flux, the effect of which only becomes of importance in slotted armatures. The first two are easily allowed for. The lost volts at full-load are evidently

Output of the machine in kilowatts.	Lost volts as a percentage of full-load pressure.	
	Shunt machines.	Compound machines.
5	7	10
10	6	8
·25	5	7
50	4	6
100	3½	5
200	3	4
500	2½	3
1000	2	2½
2000	1½	2

$$e = (C_a \times r_a) + (C_a \times r_s),$$

the last term not being required in the case of series machines. Adding this quantity to the ordinate O V we obtain O E as the pressure that must actually be generated in the armature, and this requires an excitation of X_2 ampere-turns. As it is frequently convenient to check the dimensions of an armature conductor in a preliminary design by means of this quantity, the table appended below, giving average values of e, may be of use in this direction.

With regard to the demagnetizing ampere-turns of the armature, we know generally that these are the ampere-turns lying in the angle of brush lead. Assuming that the brushes will be set just under the pole-tips at full load, the demagnetizing turns are given by *number of conductors lying between the adjacent pole corners multiplied by the current in them.*

These ampere-turns we multiply by the dispersion co-efficient v, because they have to be neutralized on the field system, then add the result to X_2, and set them off as X_3; and by projecting this value up to the curve and across, find the point E_1.

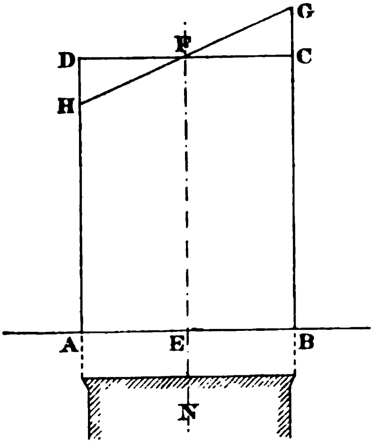


FIG. 386.

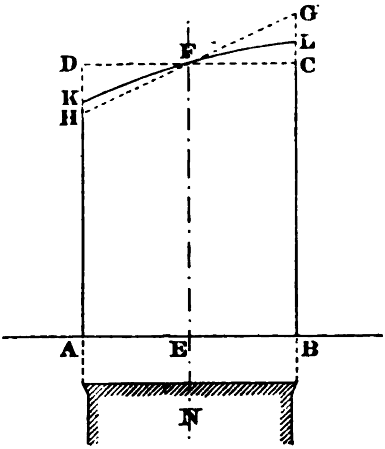


FIG. 387.

Now with a smooth core armature, the distortion of the flux in the air-gap does not produce a pressure-drop. In Fig. 386 let A B represent the width of the pole-face to scale, and E F the flux-density in the air-gap B_g. Then the area A B C D is proportional to the useful flux N_a, and at no-load we may regard this flux as being distributed uniformly along the air-gap as indicated by the rectangle. But at full-load the flux is heaped up at the forward pole-horn and withdrawn from the hindward horn, as indicated by the figure A H G B, and as the permeability of the air-gap is constant, the area of this figure is equal to the area of the rectangle A B C D. For instance, if X_g are the ampere-turns required for the air-gap (flux-density = B_g), and X_d are the ampere-turns lying under the poles and producing the distortion, we have

Line F E proportional to X_g;
„ A H „ $X_g - X_d$;
„ B G „ $X_g + X_d$;

and consequently no diminution of the total flux takes place in a smooth core armature.

We see then that Fig. 385 gives us the compounding for a machine with such an armature. We see that if the load were switched off (the speed remaining the same) the volts at the terminals of the machine would rise from the value O V to that of O E_1. Consequently the compounding ampere-turns are given by $(X_3 - X_1)$, and the shunt ampere-turns by X_1. If the machine were merely shunt-wound, it would require to have inserted in the shunt-circuit a regulating rheostat which could be adjusted to give X_1 ampere-turns at no-load, and X_3 ampere-turns at full-load.

But for toothed armature machines there must be made an allowance for the distorting effect, due to the fact that the permeability of the teeth is not constant. As before, let (in Fig. 387) the rectangle A B C D be proportional to the useful flux, E F representing the flux-density B_g in the air-gap. If the teeth were of constant permeability, the flux from the pole-face could be regarded as being of the same value as at no-load, but distributed differently, as shown by the figure A B G H. But the increased flux-density at the forward pole-horn causes the permeability of the teeth at this point to have a much lower value than they have with the flux-density B_g, while, on the other hand, the permeability of the teeth under the hindward horn has increased on account of the diminished flux-density in them. As a result, the line H F G takes a bent form as shown by the curve K L; and *the shape of this curve is the same as that of the saturation curve over* *this range.* As can readily be seen from the figure, the area A K L B is considerably less than the area A H G B, that is, there is a diminution of the useful flux N_a, and consequently a corresponding pressure-drop, and the diminution will be as a rule greater, the greater the flux-densities in the teeth.

One way of estimating the number of compensating ampere-turns required to overcome the effect produced by the distortion of the useful field is as follows. In Fig. 388 let

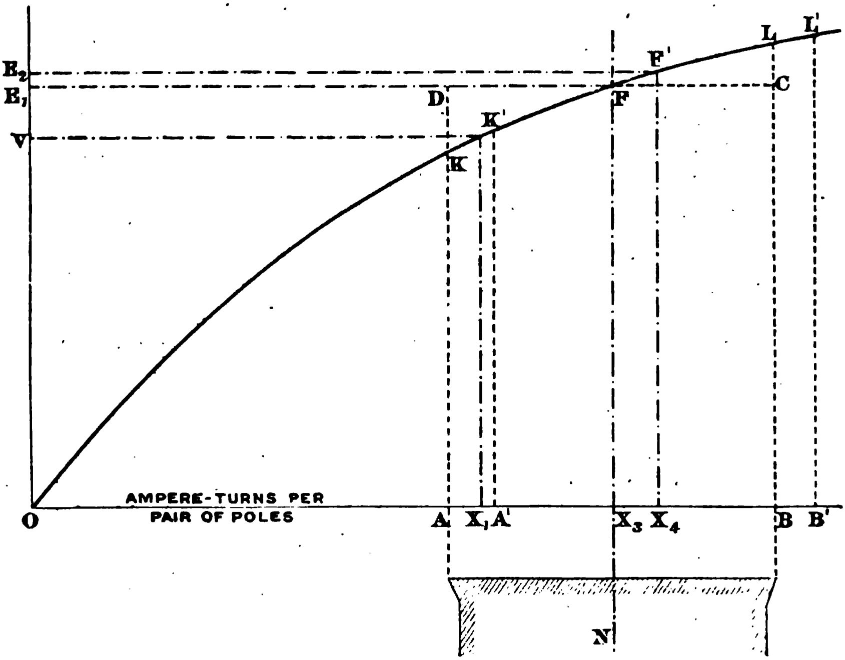


FIG. 388.

O L be the saturation curve of the machine, the ampere-turns required for no-load, and for the full-load induced electromotive force on no-load (and, therefore, without the extra allowance for distortion), being set off upon its scale of abscissæ O X as X_1 and X_3 respectively, these being estimated as shown above. Now mark off

$$OA = X_3 - X_d; \quad OB = X_3 + X_d$$

upon O X. The point A then represents the hindward pole-horn, and point B the forward pole-horn. Had distortion been absent, the ampere-turns required to produce E_1 volts would have produced a flux across the gap proportional to the area of the piece A B C D. But as distortion is present, the flux is proportional to the smaller area A B L K. All we have to do now is to shift the point F higher up the curve to a point such as F′, so that the area A′ B′ L′ K′ becomes equal to the area A B C D. This gives a new point X_4 along O X, representing the full-load ampere-turns required. Consequently, we see that, if the machine is compound-wound, the series ampere-turns must be $X_4 - X_1$, and the shunt-turns X_1 in order that the terminal volts may be O V at full-load. If a shunt machine, the resistance of the shunt rheostat must be capable of reducing X_4 ampere-turns to X_1 ampere-turns. If the machine had no shunt resistance, then the drop from full-load to no-load would be ($O E_2 - O V$) at constant speed.

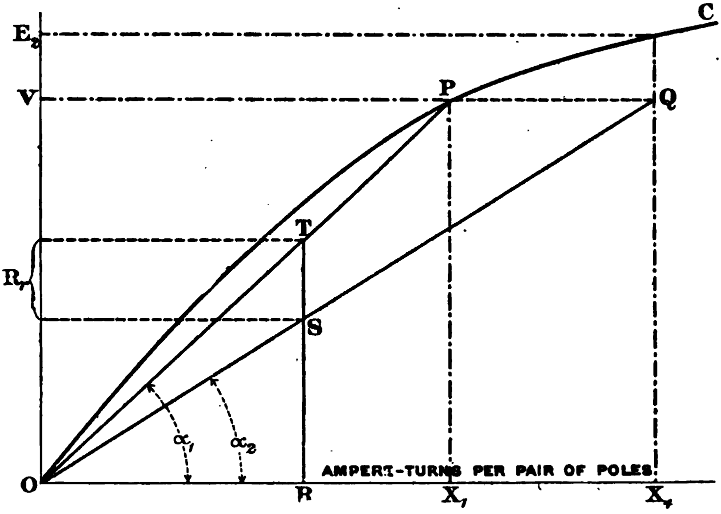


FIG. 389.

It is unnecessary to say that the above methods of predetermining the pressure-drop and amount of compounding will not give an exact result. Such a result would be quite impossible to arrive at by any process of calculation only and as a matter of fact great accuracy is not required. If the machine is shunt-wound, the regulating rheostat will in practice have sufficient margin each way to cover the inaccuracy, while compound windings are in practice adjusted in the test-room by the method of experiment. It becomes, therefore, necessary only to predetermine the pressure-drop from the point of view of the winding space required on the magnet bobbins, and from this point of view the above method will be found to give extremely good results.

Resistance of Shunt Regulator.—Knowing the values of X_1 and X_4 as found above (X_1 and X_3 for machines having smooth core-armatures) it is a simple matter to determine the necessary resistance for the shunt regulator. Let, in Fig. 389, O C be the no-load curve of the machine, the no-load and full-load ampere-turns being given by X_1 and X_4, respectively. Then we have to find the value of shunt regulating resistance in order that the machine may deliver current at the constant electromotive-force O V; it being assumed that the regulator is to be short-circuited at full-load. First, obtain the points P and Q by projection, and join O P and O Q.

Let the number of shunt turns be denoted by S_{sh}.
Then shunt current at no-load $= X_1 \div S_{sh}$;
and " " " full " $= X_4 \div S_{sh}$; hence

$$r_{sh} = \frac{S_{sh} \times OE}{X_1} = \tan a_2,$$

$$r_{sh} + r_r = \frac{S_{sh} \times OE}{X_4} = \tan a_1.$$

Along O X mark off a piece O R equal to the number of shunt turns S_{sh} and to the same scale as X_1 and X_4, etc. Erect a perpendicular R T. Then

$$\frac{r_{sh}}{r_{sh} + r_r} = \frac{RS}{RT}.$$

That is (R T − R S) gives directly the value of r_r in ohms, it being read off from the scale of electromotive-force, as indicated by the figure.

In Chapter XXVI. on *Regulating Rheostats* will be found some useful methods for designing these appliances, and a Table of the alloys suitable for their construction.

The Adjusting Shunt.—To adjust the operation of compounding coils, they are often shunted with an iron resistance. As the load rises this shunt heats, and its resistance rises relatively to the compounding coils of copper, so increasing the compounding at the maximum load.

Inherent Regulation.—One way of considering the regulating properties of a machine, is to observe by experiment (or calculate from the saturation-curve) how many volts the potential will rise if, being excited with the full ampere-turns necessary to give no-load voltage at the terminals under full-load, the excitation is maintained, but the load taken off the armature. The resulting percentage rise of voltage may be called the *inherent regulation*, as distinguished from *pressure-drop*.

CHAPTER XVIII.

THE DESIGN OF CONTINUOUS-CURRENT DYNAMOS.

DYNAMO design is an art not to be acquired without practice and experience; and like other branches of engineering design it reposes upon fundamental scientific principles, which can be laid down definitely, and taught with precision. But in the application of them in design to meet the varied needs of an ever expanding industry there is wide scope for choice and for individual preference. Time and experience have indeed taught the general lines along which dynamo design must proceed. But no one yet ever designed a successful dynamo by mere rules. A grasp of principles, electrical and mechanical; a knowledge of machinery and its construction; an acquaintance with the successful forms that exist; and a perception of the reasons why they are successful;—these and many other things are requisite in the designer who is to produce machines that will hold their own in the competition of to-day. The art of design needs the eye to see as well as the mind to understand.

The calculations and formulæ required by the dynamo designer have been already mostly given and explained in the preceding Chapters. A careful study of these, and the detailed calculations given of the representative machines in the present chapter, will make the methods adopted in designing continuous-current dynamos sufficiently clear. Beyond giving a number of working data, and an order of working that may be adopted in designing, we shall rely upon the worked-out examples of the succeeding chapter to give the reader an insight into the methods of dynamo design. It would be useless to do otherwise, as so much depends upon the skill and experience of the designer, the type of the machine, and the conditions of the specification as to speed, output, voltage, regulation, and heating limits to which he is obliged to conform, that no hard-and-fast rules applicable to every case can possibly be given. The following remarks and working constants are to be taken as applying only to modern machines of fair and large sizes—that is, to slotted drum armatures with multipolar field-magnets, which are assumed throughout, except where anything is explicitly said relating to other types.

There are two principal ways of designing a dynamo to fulfil specified conditions as to freedom from sparking, heating and efficiency; the output, speed and voltage being assumed to be the same in each case. With a given number of poles on the field-magnet frame, and of conductors upon the armature, the effects of armature reaction may be kept down either (1) by working the teeth at normal flux-densities (say 100,000 lines per square inch, and under) and with a wide air-gap, or (2) by forcing the magnetism of the teeth to values exceeding 110,000 lines per square inch, and working with a smaller air-gap; the high reluctance of the teeth with such large magnetic densities acting like an extension of the air-gap. The former method corresponds to Continental practice, and the latter to American practice in continuous-current dynamo building. It would appear that the second method is considerably the better from the point of view of avoidance of sparking (both being the same with regard to efficiency and heating), and therefore we adopt it here, as giving a better commercial machine.

There is another aspect in which the plans followed in designing may differ. One may begin by following general experience as to speeds, sizes and electrical proportions, and having proceeded to sketch out the main features of the design, may then proceed to calculate the power wasted as heat in the various parts, and so estimate the efficiency, and then, after so finding the various items of heat-waste, return and amend the first calculations according as to whether we have found any part to heat too much or too little. Or, instead, one may begin, as the result of experience, to assume and allot in advance the various permissible losses of power in the various parts—so many watts in the iron core, so many in the armature copper, so many in the field-magnet coils. One will then have a definite idea as to how much cooling surface will be necessary, and what will be the allowable current-densities in the copper and flux-densities in the iron. This procedure settles many points in advance. Similar considerations have long governed the design of transformers, and their advantage has gradually been acknowledged by dynamo designers. If the permissible losses are thus generally assumed in advance, and the designer concentrates his efforts on the securing of perfect sparkless commutation, he will generally find that such a design is satisfactory from the efficiency point of view. Whereas if he assumes generalities about commutation and concentrates his attention only on the questions of efficiency, he may find his design very unsatisfactory from the point of view of faultless performance. The development of the subject of late has much simplified the preliminary procedure; and though detailed calculations need to be repeated to observe the effect of small modifications, there ought now to be no uncertainty about the main features of any required design.

In another respect also dynamo design has developed. Formerly the dynamo designer built his machines without knowing the precise voltage which they would give at any particular speed, and left the speed to be determined by trial after the machine should have been completed; then adding a pulley of such size as would suit the conditions of driving. But now-a-days, when nearly all dynamos are direct-driven from engine or turbine, the speed is prescribed beforehand by conditions fixed by the steam-engine builder or the turbine-constructor. Therefore now all dynamo design proceeds on the supposition of a prescribed speed, a prescribed voltage and a prescribed normal output of current.

RELATION OF SIZE TO OUTPUT AND SPEED.

Speeds.—In designing a series of dynamos of different outputs from small to large, it must be remembered that engine-conditions govern the selection of speeds, and that it will not do to assume that a 1000-kilowatt dynamo can run at the same speed as a 10-kilowatt dynamo. Neither will it do to assume that the speed may be varied inversely[1] as the number of kilowatts. A rule more near to practice is that in a series of steam-engines of given type, the speeds vary about inversely to the square root of the normal full-load. If a 10 horse-power engine runs at 800 revolutions per minute, then an engine of 1000 horse-power will not run at $\frac{1}{100}$ of the speed, but at about $\frac{1}{10}$ of the speed, namely 80 revolutions per minute.

As for the relation between the size of the armature and the speed, it must be remembered that for a given angular velocity the centrifugal force per pound of matter at the periphery is directly proportional to the radius; while for a given peripheral velocity the centrifugal force per pound of matter at the periphery is inversely proportional to the radius. Considerations as to binding wires, and ability generally to withstand centrifugal strains will therefore dictate that machines of large diameter must run with a lower number of revolutions per minute, but may run with higher peripheral speeds than those of smaller diameter. In fact the customary peripheral speeds may be expressed by some such formula as

$$\textit{peripheral speed} \text{ (in ft. per min.)} = a \times \frac{kw}{kw + b};$$

where a and b are coefficients, of which the values are for a about 4500, and for b from 150 to 300. Some makers adopt designs outside these limits; but the majority fall within. They yield the following values:—

---

[1] If this might be assumed, the design of a series of dynamos would be much simplified, as the late Prof. S. H. Short has shown, since then all armatures might be made of same axial length, and all field-magnet poles of same size, the number of them being simply increased, 4, 6, 8, 10, 12 or more, in simple proportion to the required normal output.

Kilowatts .	50	100	200	300	400	500	1000	1500	2000
Peripheral speed in feet per min.	640 to 1125	1125 to 1800	1800 to 2570	2250 to 3000	2570 to 3270	2810 to 3450	3450 to 3900	3750 to 4100	3900 to 4180

These are safe numbers to use in preliminary design; but it must not be assumed that an experienced designer will not go outside them. In fact there are two classes of machines in which of necessity the peripheral speeds lie outside these limits, namely (1) *steam-turbine dynamos*, in which the peripheral speeds go far above; and (2) *exciters*, mounted on the shafts of large alternators, in which the peripheral speeds are far below those here assigned as ordinary.

Size and Output.—It is customary to express the relation between the dimensions of an armature and its normal output by reference to *output-coefficients.* The output of an armature of a given size, running at a given speed in magnetic fields of a given intensity, is nearly independent of the number of poles, but depends upon the diameter d of the core-body and upon the length l (*i.e.* the gross length between the core-heads) of the core-body parallel to the axis. It is found in practice that the permissible normal output (fixed by considerations of heating and of sparkless collection) is not strictly proportional either to the volume of the armature, or to its peripheral surface. The formulæ that have found favour for preliminary design are of two kinds, being based on the assumption that the output of an armature can be expressed in terms of *volume* or of *surface.* Of the first kind is the formula of Esson,[1]

---

[1] Esson: On the Design of Multipolar Dynamos, *Journ. Inst. Elec. Engineers*, xx. 272, April 9, 1891, where the matter is given in the form:—

$$\text{Watts} = 0{\cdot}072\, d^2\, l\, n$$

for drums; or for ring-armatures

$$\text{Watts} = 0{\cdot}048\, d^2\, l\, n\,;$$

where d and l are in centimetres and n is the revolutions per second. This formula Esson deduced on the assumption that $\mathfrak{B}_g = 5000$, and that the ratio of pole-arc to pole-pitch is 0·71.

which puts the product $d^2 l$ as proportional to the output and inversely proportional to the speed. Of the second kind is the formula of Steinmetz,[1] which takes the product $d\,l$ as proportional to the output simply. In each case then, the quantities are connected by an output coefficient; and in each case the coefficient is not a constant, but varies for different types and sizes of machine.[2]

Esson's Coefficient.—Following Esson, we may state the relation in the following manner:—

$$d^2 l = \kappa \times \frac{kw}{\text{revs. per min.}}; \qquad . \qquad [\text{I}]$$

where κ is the output coefficient. As machines were constructed in 1891, the value of κ when d and l are expressed in inches was about 76,200 for drum-armatures, and about 51,000 for elongated ring-armatures. With the improvements of time machines of equal output can now be made to give the same output at the same speed, and the most recent values are considerably lower.

According to E. K. Scott[3] modern practice yields the following values:—

Largest fly-wheel dynamos	30,000
Large multipolar ,, ...	33,000
Small ,, ,, ...	55,000
Large bipolar ,, ...	70,000
Small ,, ,, ...	140,000.

A formula given by Kapp[4] is equivalent to the above, and

---

[1] See the author's *Polyphase Currents* (edition 1901), p. 262.

[2] Rothert puts this formula into the shape also used by Fischer-Hinnen:

$$d = \text{A}\sqrt[3]{\frac{\text{E C}}{r.p.m. \times \lambda}};$$

where A is proportional to the cube-root of the constant κ, and λ stands for the ratio l/d, which is assumed from the number of poles.

[3] *Journ. Inst. Elec. Engineers*, xxxii. 362, 1903.

[4] *Elektromechanische Konstruktionen*, Berlin, 1902, p. 16, where the formula is given as:—

$$\text{Kilowatts} = \text{C}\left(\frac{d}{100}\right)^2 . \, l \left(\frac{\text{U}}{100}\right);$$

where d and l are in centimetres; U the revs. per min.; and C a factor which varies from 0·5 for small ring machines to 2·5 for large drum machines.

yields values for the coefficient varying from 25,000 for large drum machines to 125,000 for small ring machines.

The value of κ is by no means a constant, even for machines of similar type by the same makers, but varies (for reasons which will later be explained) with the size of machine. By the kindness of Mr. Kolben the author is able to give in Fig. 390 a diagram which shows the variations found in a standard series of machines constructed by Kolben & Co. It appears[1] that for a 10 *kw* machine $\kappa = 65{,}000$; for a 100 *kw* machine $\kappa = 42{,}000$; for a 275 *kw* machine $\kappa =$ 30,000. Mr. Blood of Boston uses as a criterion the figure 30,000, and considers machines over-rated if κ falls below the value 30,000.

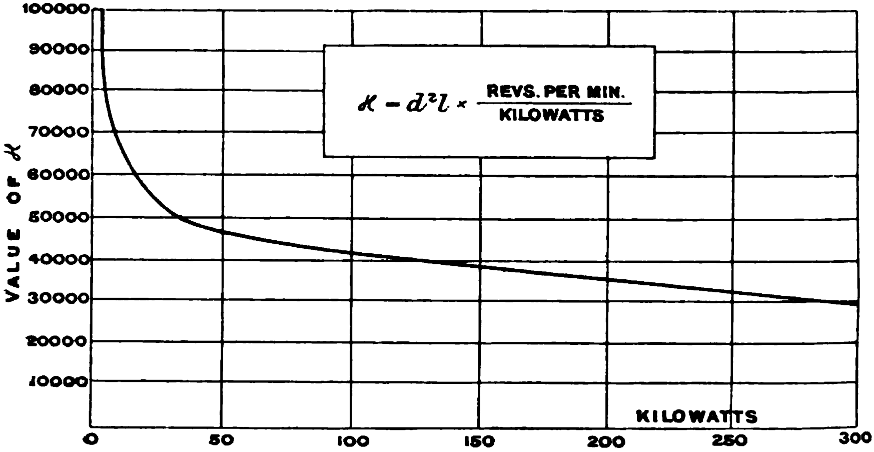


FIG. 390.—VARIATIONS OF OUTPUT COEFFICIENT.

Steinmetz's Coefficient.—The simplest of all such empirical rules is that of Steinmetz, that the product of the diameter of the iron core-body into its length is proportional to the output. Accordingly, we have the relation :—

$$d\,l = \sigma \times kw \; ; \qquad . \qquad . \qquad [\text{II}]$$

---

[1] See also the remarks by Eborall, Mavor and Ledward in the discussion of the papers of Mr. Esson and Mr. Scott in *Journ. Inst. Elec. Engineers*, xxxii. 302–469, 1903.

where, if d and l are expressed in inches the value of σ the Steinmetz coefficient will not differ much from 3. In old machines and machines of relatively small output, or of slow speed, the value[1] of σ may go up to 5 or 6; for large and well-designed machines it may fall below 2. Of the various machines mentioned in this book the lowest value of σ is 1·44, being that of the Hobart design of 1600 *kw.* p. 695, while the highest is 13·4, being that of the very slow-speed exciter of Kolben & Co., p. 673.

Ratio of Diameter to Length.—Having thus obtained, by one or other of the above rules, a trial-value for a product

---

[1] If d and l are given in millimetres, the values of σ will range at about 2000, going down in large modern machines to 1250, or going up in small and slow-speed machines to 3500 or 4000.

There is a rational basis for this Steinmetz coefficient, for if it is assumed that there is a best average peripheral speed for the conductors moving in a field of best average density, and that there is a fixed limit of temperature rise and a fixed ratio for the armature losses to the normal output, then the output ought to bear a constant ratio to the *working* surface of the armature—therefore proportional to $d \times l$.

Let v be the peripheral speed in inches per second, B the average flux-density (in lines per square inch) in the air-gap, ψ the ratio of pole-span to pole-pitch, W the full-load output in kilowatts, q the number of ampere-conductors per inch periphery, then the total polar area surrounding the armature is $\pi \times d \times l \times \psi$ square inches. Now all the work done by the machine takes place under the poles; and we may write

$$\text{Work done per second} = \text{peripheral force} \times \text{peripheral velocity},$$

which may be written

$$\text{Output} = \text{force per unit surface} \times \text{total active surface} \times \text{peripheral velocity},$$

or

$$= \mathrm{B} \times q \times \psi \times \pi \times d \times l \times v \text{ (ergs per second).}$$

$$\mathrm{W} = \mathrm{B} \times q \times \psi \times \pi \times d \times l \times v \div 10^{11} \text{ (kilowatts).}$$

Now assigning to B, q, ψ, and v the respective average values 50,000, 600, 0·7, and 500, values which are found in good non-sparking machines, this becomes

$$\mathrm{W} = 0{\cdot}33 \times d \times l,$$

whence

$$3{\cdot}03 = d \times l \div \mathrm{W},$$

thus arriving rationally at the Steinmetz formula. Moreover, as the value of the constant was fixed by non-sparking conditions, it is clear that the limit of the output of the machine depends on heating alone; $d \times l$ being a measure of the cooling surface. Thus under the assumption (which is found to be true in praccontaining d and l, it remains to separate out the two factors. One method of doing this is to take the highest permissible surface speed; divide it by the number of revolutions per minute and by π, thus getting the largest permissible diameter as one of the desired factors. Another guide, assuming the number of poles to be fixed, is to assume as a fair rule for cast-steel pole-cores of circular section that the length of the armature-core will be equal to half the pole-pitch at the armature surface; in which case the ratio $d/l = 2p/\pi$; whence $l = d\pi \div 2p$. Inserting this value in [1] and in [2] we get the following:—

$$d^3 = \frac{kw}{r.p.m.} \times \frac{2p\kappa}{\pi}; \qquad l^3 = \frac{kw}{r.p.m.} \times \frac{\kappa\pi^2}{4p^2};$$

tice) that the limit to the output of machines of this type is put by heating, not by sparking, it follows that the value of the constant depends almost entirely *on the peripheral speed.* That is part of the reason for the differences observed in the examples given above, and furnishes a strong argument in favour of *high peripheral speeds*, and therefore of armatures tending toward the fly-wheel type.

Kapp's rule given above, if transformed in terms of British units (d and l in inches, and peripheral speed v in feet per minute), comes to this:—

$$d \times l = W \times \frac{c}{v};$$

where W is the full-load output in kilowatts, and c a coefficient which varies between the values of 35,000 for small ring-wound machines and slow-speed machines down to 7000 for large well-ventilated drum-machines.

Examples.	Kilowatts.	Steinmetz Coefficient.
Multipolar generator, Engl. El. Mfg. Co., p. 691 .	1100	1·96
„ „ Hobart's design, p. 695 . .	1600	1·44
„ „ „ . .	400	3·7
„ „ Siemens & Halske, p. 699 . .	1000	2·16
„ „ Brown, Boveri & Co., p. 609 .	480	2·25
„ „ „ „ p. 660 .	194	2·47
„ „ Kolben & Co., p. 671 . .	250	4·35
„ „ Walker Co., p. 595 . . .	440	3·6
„ „ Gen. Elect. Co., p. 678 . .	550	3·57
Bipolar „ Johnson & Phillips (1887) p. 621 .	21	8·4

and

$$d^2 = \frac{kw \times 2p\sigma}{\pi}; \qquad l^2 = \frac{kw \times \pi\sigma}{2p};$$

from either of which d and l can be determined.

If the pole-cores are to be constructed of stampings, then, assuming that l will be equal to the pole-span, and that the latter is equal to the pole-pitch multiplied by the coefficient ψ (of about 0·7 in value), then $l = d\pi\psi \div p$, and similarly inserting in [1] and [2] we deduce :—

$$d^3 = \frac{kw}{r.p.m.} \times \frac{\kappa p}{\pi\psi}; \qquad l^3 = \frac{kw}{r.p.m.} \times \frac{\kappa \pi^2 \psi^2}{p^2};$$

and

$$d^2 = \frac{kw \times p\sigma}{\pi\psi}; \qquad l^2 = \frac{kw \times \pi\sigma\psi}{p}.$$

Rational Formulæ for Output.—As the author has elsewhere[1] shown, a formula involving no arbitrary constants can be deduced from first principles. In the following argument B_g stands for the mean flux-density at the pole-face, l for the gross length of the armature-core, which is taken as equal to the length of the pole-face from front to back ; ψ the ratio of the equivalent pole-span to the pole-pitch ; q_1 the number of ampere-conductors per unit length of periphery or "specific load." Then, since the flux from one pole is equal to B_g multiplied by the pole-face area, we have : —

$$N = B_g \times d \times \pi \times \psi \times l \div p.$$

Further, if C be the whole current of the armature, and c the number of armature circuits, $C \div c$ is the current in one conductor. Hence multiplying this by the number of conductors Z we find the whole number of ampere-conductors all round the armature, which we may equate to the product of q_1 into the periphery, and so deduce :—

$$Z = q_1 \times d \times \pi \times c \div C.$$

Now, the general formula for continuous-current machines see [I*a*] p. 282) may be written

$$E = \frac{p}{c} \times \frac{r.p.m.}{60} \times Z \times N \div 10^8.$$

---

[1] *Journ. Elec. Inst. Engineers*, xxxii. 445, Jan. 1903.

Inserting into this formula the values of Z and N obtained above, and writing E × C ÷ 1000 = *kw*, we get:—

$$d^2 l = \frac{60\cdot 8 \times 10^{10}}{B_g \times q_1 \times \psi} \times \frac{kw}{r.p.m.} \quad . \quad . \quad [\mathrm{III}]$$

This formula[1] is equally true whether inch-units or centimetre-units are adopted. It shows at once why the output-coefficient κ (p. 538), is not constant. For it we may write:—

$$d^2 l = \kappa \times \frac{kw}{r.p.m.}; \quad . \quad . \quad [\mathrm{IV}a]$$

[1] From this, expressions for d may be deduced by assuming suitable values for d/l.

For cylindrical cast-steel pole machines, where $l = a\pi \div 2p$,

$$d = 7290 \times \sqrt[3]{\frac{kw \times p}{r.p.m. \times B_g \times q_1 \times \psi}} \text{ (in inch measures)};$$

or for laminated pole-cores giving square face, where $l = d\pi\psi + p$

$$d = 5787 \times \sqrt[3]{\frac{kw \times p}{r.p.m. \times B_g \times q_1 \times \psi^2}}.$$

For a discussion of the $d^2 l$ formula, see Arnold in *Electrot. Zeitschr.*, xxiv. 285, Ap. 6, 1903; and Rothert, *ibid.* xxiv. 405, May 21, 1903. Arnold remarks that the constant κ may be lowered by the use of a larger quantity of copper on the field-magnet. Rothert observes that the smaller κ the smaller will be the pole-surface, and the higher will be the flux-density in the gap, and that necessitates longer and heavier poles. This is the explanation of the paradox that for small 4-pole machines of less than 3 or 5 kilowatts, the armature must be designed large if the whole machine is to be made small. In a series of machines the constant does not necessarily diminish as the kilowatts increase, because at the point where one changes from a 4-pole machine to a 6-pole machine, the gap-density in the small 6-pole machine will be lower than that in the 4-pole machine of equal normal output, and for the former the value of κ will be greater, not less, than for the latter. Rothert gives for the value of κ for a 100-kilowatt machine, 350,000, when d and l are in centimetres; for a 1000-kilowatt machine at 180 revs. per min., 270,000. In these calculations the l is taken by Rothert not as the gross length between the core-heads, but as the gross length less the air-ducts. As he recommends in design a gap-density of 11,200 to 12,300 lines per square centimetre (corresponding to B_g = 72,000 to 89,000 per square inch), and a value of q_1 exceeding 650 amperes per inch periphery, his machines are unusually small for their output.

Another discussion of output formulæ is by R. Bauch, in the *Zeitschrift für Elektrotechnik und Maschinenbau*, 1899, p. 463. His method has been adopted by Bradwell in his work *Dynamo-Maschinen*, Potsdam, 1902.

in which

$$\kappa = \frac{60 \cdot 8 \times 10^{10}}{B_g \times q_1 \times \psi} \quad . \quad . \quad . \quad [\text{IV}b]$$

If we insert typical numerical values, we may take B_g not *less* than 45,000 lines per square inch, q_1 not more than 600 per inch of periphery, and ψ at 0·70. Putting in these figures we find

$$\kappa = 32{,}000.$$

In the cases mentioned above the factor κ was found to be for bipolar machines as large as 70,000, or even higher. It is clear that there is a bad utilization of material; the factors B_g, q_1, and ψ of the divisor being low. The reason why (as is seen in the curve Fig. 390) the factor κ is smaller for large machines than for small ones, is that in the large machines it is possible to work with higher pole-face density, or with a greater specific load (per inch periphery) on the armature. *To make a machine that is small in volume* (and therefore in *cost* of materials) *for its output, it is essential that the three quantities* B_g, q_1, and ψ *should be each as high as possible.*

It is possible to apply similar reasoning to find a rational value for σ, the Steinmetz coefficient. Writing v for the peripheral speed in feet per minute, we have :—

$$12\,v \div \pi d = \text{revs. per min.};$$

if d is in inches. Inserting this value in [III], cancelling d from both sides and rearranging, we get

$$d'' \times l'' = \sigma \times kw \qquad [\text{V}a]$$

where

$$\sigma = \frac{15 \cdot 9 \times 10^{10}}{B_g \times q_1 \times \psi \times v}; \quad . \quad . \quad [\text{V}b]$$

so that if these various quantities are known from experience a suitable value for σ can be at once found for any case that may arise, and so the proper size of the armature may be at once determined.

By inserting appropriate values of v (see p. 536) in the foregoing formula, we may deduce an approximate equation

$$\sigma = 2 \times \frac{kw + 150}{kw}.$$

These values are plotted in the curve, Fig. 391. In practice mean values of σ agree with this curve.

For 500-volt machines it is found that the diameter in inches, is nearly equal to the kilowatts divided by the mean number of volts per segment of the commutator.

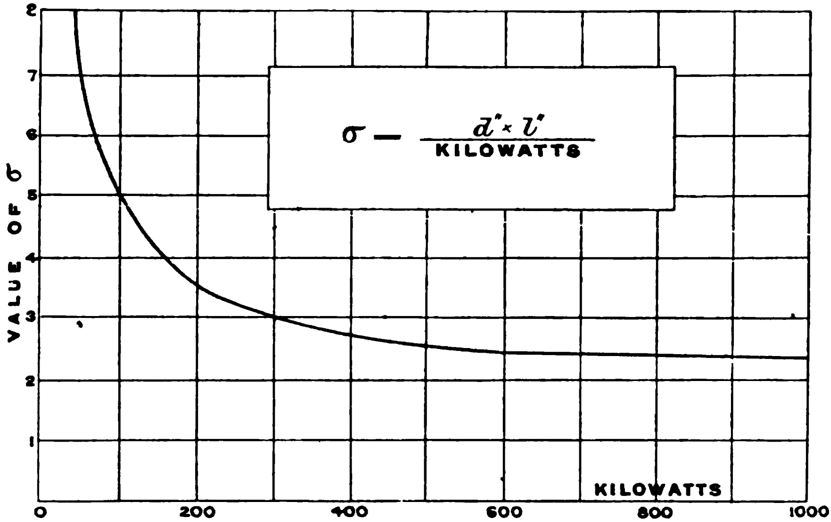


FIG. 391.—CURVE OF VARIATION OF STEINMETZ COEFFICIENT.

It must be understood clearly that the application of such formulæ as the foregoing is to obtain *trial-values* of *d* and *l* which are subject to modification and adjustment to meet subsequent points that arise in the design.

WORKING CONSTANTS AND TRIAL VALUES.

(*a*) *Flux-densities.*—As average values for the magnetic densities in the various parts of the machine at full-load, we may take :—

Flux-density in—	Lines per square inch.	Material.
Armature body . .	60,000	sheet iron or steel stampings.
,, **teeth** .	130,000	,, ,,
Air-gap . . .	45,000 to 55,000	air.
Magnet cores . .	75,000 to 100,000	cast steel or wrought iron.
,, **yoke** . .	70,000 to 100,000	,, ,,
	35,000 to 50,000	if of cast iron.

For sparkless commutation, the density in the armature-teeth must not differ very much from the above value. Mr. H. S. Meyer recommends an apparent density of 140,000 to 155,000. The density in the armature core-body should be less, and is determined by the permissible iron-loss.

(*b*) *Current Densities.*—As an approximate guide to the sizes of the conductors required for the different parts, we may take :—

Current Densities.	Amperes per Square Inch.	Square Mils per Ampere.	Circular Mils per Ampere.
In armature conductors . .	1500 to 2000	667 500	847 637
In commutator risers . . .	2400 to 4000	417 250	531 318
In field-magnet coils . . .	600 to 800	1670 1250	2126 1591

The section is, of course, finally determined by the permissible heating and voltage-drop. For field-magnet windings see the rules in Chapter VII. pp. 179 to 185 ; if the cores are cylindrical and fairly long, the density may even reach 1000 amperes per square inch.

(*c*) *Number of Poles.*—There are two ways of settling the appropriate number of poles, one depending on the prescribed speed as it affects the frequency of magnetic reversals, the other depending on the prescribed output of current.

(1) In order to keep down the iron losses the frequency of magnetic reversal should be kept down under 20 reversals per

second, except for over-compounded machines when 22 is a permissible figure. Excellent machines are made with lower figures, down to 12 or 15, but they will be heavy for their output. Since the magnetism of any part of the armature-core goes through a reversal as it passes each pole, the number of poles will be roughly inversely proportional to the speed. As a trial value we may set:—

$$p \geqq \frac{1080}{r.p.m.} \quad . \quad . \quad . \quad [\text{VI}a]$$

(2) The second criterion[1] is the prescribed output of current, since, to avoid sparking troubles, it is wise not to attempt to collect more[2] than 200 amperes at any one row of brushes. As in lap-wound armatures the number of rows of brushes in either the positive or the negative set is equal to the number of pairs of poles, the total number of rows of brushes will be the same as the number of poles. Hence it follows that a trial value as to the proper number of poles can be found by dividing the prescribed full-load current by 100, or—

$$p \gtreqless C \div 100. \quad . \quad . \quad [\text{VI}b]$$

Thus, if the machine is to give 950 amperes, 10 poles will be adequate. (Special machines, such as electrolytic machines and very slow-speed exciters to be mounted on the shafts of large alternators, are exceptions.) In general this rule gives too few poles for the smaller sizes, and too many for the larger sizes of dynamo.

---

[1] Wiener (*Practical Calculation*, 2nd edition, 1902, p. 287*a*) advises to make the choice of poles depend *only* on the speed, the object being to limit the number of reversals of magnetization per second in the armature-core, and so keep down the armature iron-losses. He states the number of cycles per second at 10 to 15 in slow-speed machines, increasing to as many as 25 or even 35 in high-speed machines. His rule is equivalent to saying that for slow-speed machines one can find the appropriate number of poles by dividing the number of revolutions per minute into 1200 or 1800, and taking the nearest even integer higher than the quotient. But such a rule leaves out of sight the size of the machine: and it would be absurd to give the same number of poles to a 40-kilowatt and to an 800-kilowatt machine, simply because each of them ran at, say, 120 revolutions per minute. Fischer-Hinnen (*Continuous-Current Dynamos*, 1899) recommends 4 poles as appropriate for machines between 6 or 20 kilowatts and 100 or 150 kilowatts; and 6 poles as appropriate up to 200 or 300 kilowatts.

[2] Nevertheless satisfactory machines exist with fewer poles than by this rule; for example, the Berlin generators of the A. E. Gesellschaft, giving 2600 amperes and having only 18 poles, and the 6-pole generators of the Oerlikon Company, at the Volta Company in Rome, giving 1500 amperes. Brown's 8-pole electrolytic machine, Plate VIII., has an output of 4000 amperes.

(3) Another criterion is this. With such values for flux-density as are taken above, the armature ampere-conductors per pole, at full-load, should not much exceed 14,000. To get a rough idea of the number of poles required, we simply multiply the total number of the conductors, Z, around the armature by the full-load current in each, divide the product so obtained by 14,000, and take the nearest even integer as the number of poles.

$$p = Z \times C_1 \div 14{,}000. \qquad . \qquad . \ [\text{VI}c]$$

But this assumes the number of armature-conductors to be known. We may however use this rule to test the choice of Z.

(4) Another rule for finding the appropriate number of poles for large machines is to divide the kilowatts by 100, add 3, and take the next higher even number.

(*d*) *Magnetic Flux per Pole.*—If d, l and p have been found, then a trial value for N can be obtained by assuming proper values for B_g and for ψ (say 45,000 for B_g and 0·75 for ψ); since the pole area $= d \times \pi \times \psi \times l \div p$.

$$N = B_g \times d \times \pi \times \psi \times l \div p. \qquad [\text{VII}a]$$

The value so found will require adjustment after Z has been determined. To adjust it we have the formula :—

$$N = \frac{E \times 10^8}{n \times Z}; \qquad . \qquad . \qquad [\text{VII}b]$$

or, for wave-windings,

$$N = \frac{E \times c \times 10^8}{n \times p \times Z}. \qquad . \qquad [\text{VII}c]$$

The following are rational formulæ of great use :

$$N = \frac{Kw}{v \times c \times q_1} \times 50{,}000 \times 10^6 \qquad . \qquad . \qquad [\text{VII}d]$$

$$N = \frac{Kw}{r.p.m. \times c \times d \times q_1} \times 1 \cdot 91 \times 10^{12}; \qquad \text{(VII}e\text{]}$$

where v is given in feet per min., and c is the number of armature-paths.

For simple lap-windings with only 2 conductors in the loop, the following formula is accurate if the average volts per segment of commutator be known :—

$$N = \frac{\text{volts per segment}}{r.p.m. \times p} \times 3000 \times 10^6. \qquad [\text{VII}f]$$

(*e*) *Number of Armature Conductors.*—Two methods lend themselves to the fixing of a trial value for Z, one based on the diameter and permissible specific load, the other on the flux, voltage and speed.

If we adopt, under the standard conditions of design, a permissible specific load q_1 (of say 600 ampere-conductors per inch of periphery), and if there are c paths through the armature, then since each conductor carries $C \div c = C_1$ amperes, we shall have for the total number of ampere-conductors all round the armature

$$Z\,C_1 = q_1 \times d \times \pi,$$

from which it follows that Z must *not be more* than

$$Z = \frac{q_1 \times d \times \pi}{C_1} = \frac{q_1 \times d \times \pi \times c}{C_1}; \qquad [\text{VIII}a]$$

or, approximately, Z must not exceed the value

$$Z = 1885\, d \div C_1 . \qquad . \qquad [\text{VIII}b\}$$

But these rules give values that are often wide of the mark. Another, and for some purposes better rule is this:—First obtain a trial value for the magnetic flux N, and then calculate Z from the electromotive-force and speed. Using n for the revolutions *per second*, and E as the volts at no-load, the formula for lap-wound armatures is

$$Z = \frac{E \times 10^8}{n \times N} \quad . \quad . \quad . \quad [\text{VIII}c]$$

For series-parallel wave-windings this becomes

$$Z = \frac{E \times c \times 10^8}{n \times N \times p} \quad . \quad . \quad . \quad [\text{VIII}d]$$

In every case[1] the trial-number when obtained will need to be adjusted so as to give a proper multiple for winding.

Example.—Required the proper number of armature conductors for a dynamo M P 8 – 200 kw. – 375 r.p.m. – 125 v. – 1600 A. Taking the diameter of armature as 48 inches, and the trial value for the flux $N = 4 \times 10^6$; by formula [VIII*b*], the value of Z comes out 451; by [VIII*c*] it comes out 500. The actual value of Z in the machine (as built at Schenectady) was 480.

(*f*) *Number of Commutator Segments.*—This is of course equal to the number of conductors Z, divided by 2, 4, 6, etc.; in large machines almost always equal to ½ Z. The considerations which fix the number are stated on pp. 482 to 484.

A fair rule for settling the permissible number of conductors per commutator segment is that it must not exceed the value

$$\frac{Z}{K} \leqq \frac{66 \times 10^6}{l \times v_k \times q_1} \; ; \quad . \quad . \quad . \quad [\text{IX}]$$

where v_k is the peripheral speed in feet per minute.

Example.—In Brown's high voltage machine $l = 9{\cdot}85$; $v_k = 2740$; $q_1 = 300$. Hence Z/K must not exceed 8·1. The actual values were $Z = 1416$; $K = 177$.

---

[1] It is possible to assign values for N and Z without first settling *d*, by use of the formula

$$N = \sqrt{\frac{E \times B_g \times \psi \times l \times C_1}{r.p.m. \times p \times q_1} \times \frac{c}{p} \times 60 \times 10^8}\;;$$

$$Z = \sqrt{\frac{E \times p \times q_1}{r.p.m. \times B_g \times \psi \times l \times C_1} \times \frac{c}{p} \times 60 \times 10^8}.$$

(*g*) *Size of Commutator.*—As a rule it is well to take the diameter of the commutator at least ¾ of that of the armature. For large machines the diameter should be even larger in proportion, say from 12 to 16 inches smaller than the armature. Using this as a trial-value, divide the periphery by K to see whether the width of segment is suitable. This should not be less than 0·2 inch exclusive of the mica insulation, which may be taken as 0·030 inch. A mean value is 0·3 inch. Then, assuming that the carbon brushes will cover 3 segments (or in high voltage machines 3½), and that 40 amperes can be collected by each square inch of brush, find from the current to be collected at each row of brushes ($= 2 \times C_1$) the necessary net length and allow a margin for the ends of the working face. See also the formulæ on p. 484.

The result so obtained should be checked afterwards, when the watts lost in commutator heating have been estimated, by seeing whether the surface of the commutator is sufficiently large to dissipate the heat without undue temperature rise. A commutator ought to have about 0·6 square inch of peripheral surface per watt lost (compare p. 520).

(*h*) *Length of Air-Gap.*—To assign a proper length to the air-gap, it must be remembered that the air-gap in continuous-current machines, whether generators or motors, is not a mere clearance as it is in induction motors, but plays a definite part in the process of commutation. It is true that a short air-gap permits the excitation (and therefore the cost of the field-magnet) to be reduced; but a very short air-gap has the disadvantage that with any slight decentring of the armature, the latter is subject to very unequal magnetic attractions by the poles. A long air-gap, though it necessitates more excitation of the field-magnets, is of advantage in commutation as it offers an obstacle to the distorting tendency of the reacting ampere-turns of the armature. The ampere-turns that have to be provided on the magnet-pole to drive the flux across the gap are proportional to the length of the gap, and if they are relatively large, commutation is better. In this respect the ampere-turns (on the magnet core) which have to be provided to drive the flux through the (highly saturated) teeth are also helpful. Hence it is found that for satisfactory working, the ampere-turns for gap and teeth (i.e. that part of the excitation provided for these) must bear a certain proportion to the number of ampere-conductors of the armature per pole. Now, since the ampere-turns needful for the gap are proportional to the gap-length l_g and to B_g, if one can assume that those needful for the teeth are in some definite proportion to those needful for the gap (for instance are at full-load equal to 25 per cent. of the latter) then one can express the requisite gap-length in terms of the ampere-conductors per pole of the armature, and of B_g. A simple approximate rule is as follows:—

$$l_g = j \times \frac{q_1 d}{p B_g}; \qquad [Xa]$$

where j is a coefficient varying from about 4 to 8·5. The lower value is appropriate to the case where the saturation of the teeth is over 130,000 lines per square inch.

Another rule for the minimum value of l_g is:—

$$l_g = 0{\cdot}224 \times d \times l_i \div K; \qquad [Xb]$$

where l_i is the net length of iron in the armature core. The rationale of this rule is that, assuming a given specific load, and a given number of poles, the reaction per pole is proportional to the periphery and therefore to d. On the other hand, if the field is of given density, and the number of ampere-conductors round the armature a given quantity, commutation will the easier the greater K and the smaller l_i; hence the smaller K, the larger must be made the field ampere-turns per pole to resist distortion, and therefore l_g also must be larger.

For smooth-core armatures allow 1 inch for every 26,000 armature ampere-conductors per pole; or, in symbols:—

$$l_g = \frac{Z C_1}{26000 p} \qquad [Xc]$$

There is another consideration to fix a minimum for the air-gap, namely the production of eddy-currents in the pole-faces if these are not laminated. For in such cases the gap should not be less than about $1\frac{1}{2}$ times the width of the opening of the slot at the top. With laminated poles it may be less.

In designing a standard series of machines it is convenient to remember that the gap-length may have a definite ratio to the length of pole span throughout the series. With laminated pole-shoes this may be $\frac{1}{50}$, or with cast pole-shoes $\frac{1}{35}$.

Examples.—(i.) In the Oerlikon 12-pole machine described on p. 656, $d = 98\frac{1}{2}$; $l_i = 12$; $q_1 = 429$; $p = 12$; $B_g = 56{,}000$; $Z = 1326$; $K = 663$; and $C_1 = 100$. Assuming $j = 6$ equation [X*a*] gives for l_g the value 0·386; while equation [X*b*] gives 0·4 inch; and equation [X*c*] gives 0·423. The actual value was 0·394. The slot-width was 0·236. This is about $\frac{1}{45}$th of the pole arc.

(*i*) *Assignment of Losses of Energy.* — Losses in energy due to ohmic heating of the copper, to hysteresial and eddy-current heating in the iron, and to friction, are inevitable. They are discussed in the preceding chapter. Such losses must be kept down, because they lower the efficiency, and because an undue rise of temperature in any part is not permissible. Experience has shown that if a machine is to be so designed as not to overheat in any part, and to make the total loss of the minimum value compatible with economy of material, its various losses must be rightly apportioned out. The following may be taken as the apportionment of the losses in machines of different sizes :—

Output in Kilowatts.	Efficiency per cent.	Percentage Losses.				
		Armature.		Magnets.	Commutator Friction and Windage.	Total Losses per cent.
		Copper Loss.	Iron Losses.	Copper Loss.		
5 to 40	90	3·8	3·2	2·5	0·5	10
10 ,, 60	91	3·5	3·0	2·1	0·4	9
40 ,, 100	92	3·2	2·8	1·6	0·4	8
75 ,, 300	93	2·8	2·3	1·55	0 3	7
200 ,, 500	94	2·4	1·8	1·5	0·3	6
400 ,, 1000	95	1·9	1·5	1·35	0·25	5

Such a table would, however, be misleading unless it is borne in mind that the values may vary considerably even in machines of the same size for different speeds and under different conditions of working. For example, a 93 per cent. efficiency is in general too high for a 75-kilowatt machine, unless it is of very large size for its output. Such tables may however be drawn up with some accuracy for a standard series of machines of some one type, such as a series of slow-speed tramway generators, or a series of high-speed lighting machines. The following is a table of average values in a series of standard generators built by Messrs. Kolben and Co. (see p. 671).

Output in Kilowatts.	Speed.	Full-Load Efficiency per cent.	Full-Load Losses (in *watts*).			
			Excitation Loss.	Commutator, Friction and Ventilation Loss.	Copper Losses.	Iron Losses.
50	550	92·6	800	1000	1200	1000
100	450	93·0	1500	1900	2200	1900
200	350	93·4	2800	3600	4200	3600
400	300	94·0	5000	6000	7900	6800
500	100	94·4	5900	6400	9500	8000
750	100	95·0	8000	7100	13500	11000

N.B.—The first four of these machines are high-speed lighting machines, suitable for coupling direct to a high-speed engine, and the loss due to the outer bearing is included in friction losses. The last two are slow-speed traction generators; and for these the efficiency figure does not include any loss at the bearings.

Parshall gives the following apportionment for a 550-kilowatt tramway generator:—Armature copper 2·25; armature iron 2·25; magnets 0·75; commutator, etc., 0·75; total 6 per cent. Rothert gives for similar machines:—Armature copper 2·7; armature iron 1·8; magnets 1·5; commutator 0·3; total 6·3 per cent.

(*j*) *Calculation of Binding Wires.*—The method of calculation has already been laid down on p. 440, Chapter XIV.

ORDER OF PROCEDURE IN DESIGN.

The specified conditions to be fulfilled are that the dynamo, running at a prescribed speed (fixed by the choice of engine), shall give out its current at a prescribed voltage, and that when running at normal full-load of a prescribed number of amperes it shall have a prescribed efficiency.[1]

The example which is here given is continued for the remainder of this section.

Example.—To design a tramway generator to give, at 150 revolutions per minute, 600 amperes at 500 volts, the efficiency being 93 per cent.

The method of getting out a preliminary design to a given specification is, therefore, as follows :—

(1) Find the full-load kilowatts by multiplying together the volts and the full-load amperes, and dividing by 1000.

Example.—As above, 300 kilowatts.

(2) Fix a trial-value for the number of poles (see p. 546 above).

Example.—By formula [VI*a*] there are $1080 \div 150 = 7$ poles required at least. Being an odd number this is impossible: therefore take 8 poles. By formula [VI*b*], as the full load is 600 amperes, a 6-pole design would do; but to be quite sure of avoiding trouble as to sparking let us take 8 poles, so that with a parallel-wound armature there will be 8 circuits and only 75 amperes in each circuit, or 150 amperes to collect at any one row of brushes.

(3) Adopt an output-coefficient. To do this we may proceed either by Esson's or by Steinmetz's rule, and ascertain a suitable value of either κ or σ (p. 537, or p. 538). To ascertain these we must select suitable values for B_g, q_1, ψ, and v. Then having found either $d^2 l$ or $d l$, put down a number of

---

[1] Other details may be prescribed, for example, the limit to which temperature is allowed to rise, the amount to which the machine shall be compounded or over-compounded, the efficiency at ½ or ¼ load, the permissible amount of temporary overload, and the like.

trial values that will approximately fit these products, and test them by observing what surface speeds they correspond to, and what proportions as to pole-shape they yield. From these trial values select the most satisfactory.

Example.—Let $B_g = 45000$; $q_1 = 600$; $\psi = 0 \cdot 80$; and, referring to p. 536, take provisionally as a suitable peripheral speed 2450. Then by formula [V*b*], p. 543, the Steinmetz coefficient σ will be $3 \cdot 13$; whence by formula [V*a*] we get

$$d\,l = 939.$$

Or, if preferred, by formula [IV*a*], p. 542, the Esson coefficient κ comes out at 28,100, whence by formula [IV*b*] we get

$$d^2\,l = 28100 \times 300 \div 150 = 56200.$$

(4) Fix the value of *d* and *l* separately, putting down some trial-values and products from which to select.[1]

Example.—We may at once put down a number of trial values of *d* and *l* as follows:

l	d	$d \times l$	$d^2 \times l$	Peripheral Speed
12	78	936	73,008	3062
14	67	938	62,846	2631
15	62	930	57,660	2434
16	58	928	53,824	2277
18	52	936	48,672	2041

The diameter which gives us the surface speed nearest to the value of 2450 feet per minute is 62 inches. The periphery of this armature will be $62 \times \pi = 194 \cdot 75$ inches. Dividing by 8 we get the pole-pitch at the armature face as $24 \cdot 34$, and as the pole-face will cover about 80 per cent. of this, the pole-arc will be about 19 inches long; making the actual pole-face about 19 by 15 inches, which is a suitable shape for pole-cores built up of sheet iron stampings.[1] We may take it then that the values of d and l will be 62″ and 15″.

---

[1] Obviously, if we had adopted outright the surface speed $v = 2450$ then, since the revolutions per minute are 150, this would have fixed *d* at 62", and *l* would have followed as the other factor 15".

Proceeding by Esson's coefficient, the nearest $d^2\,l$ product to 56,200, amongst those set down, is 57,660, corresponding to a 62" diameter. Had we assumed that a square pole-face was desirable, we might have applied the formulæ on p. 541, and then found $d = 56 \cdot 36"$, $l = 17 \cdot 7"$.

(5) Fix a trial value for **N**. The provisional value of **N** is found by formulæ [VII] given on p. 547.

Example.—The pole-face being $19 \times 15 = 285$ square inches, if the flux-density at the pole-face be taken at 45,000 lines per square inch (a low estimate allowing for increase at full load), then **N** the flux from one pole will be about 13,000,000 lines. The rational formulæ [VII*d*] and [VII*e*] give as the value 12,800,000 lines. Or by rule [VII*f*], assuming 5 volts per segment of commutator, **N** = 12,500,000 lines.

(6) Fix the value of Z. The formulæ are [VIII*b*] and [VIII*c*], p. 548.

Example.—By formula [VIII*b*], $Z = 1885 \times 62 \div 75 = 1558$ as a maximum not to be exceeded. By formula [VIII*c*], since $E = 500$; $n = 150 \div 60 = 2{\cdot}5$; and **N** is provisionally 13,000,000, we have $Z = 1538$. Now if we desire complete symmetry, without which we cannot use equalizing rings, we ought to choose Z to be an exact multiple of the number of poles; therefore neither 1558 nor 1538 will do. But 1536 is an even multiple of 8, therefore we will fix Z as 1536. Tested by formula [VIII*a*], p. 548, it shows that the specific load will be 595 amperes per inch periphery. Let us further test it by rule [VI*c*]. If Z is right, that is, if the number of conductors per pole is not so great as to produce too great an armature reaction, then Z multiplied by C_1 and divided by p will not much exceed 14,000. Now $C_1 = 75$, and $p = 8$; and $Z \times C_1 \div p = 14{,}400$, which is satisfactory. We will therefore finally fix $Z = 1536$.

It is generally necessary after thus adjusting Z to recalculate **N** by using formula [VII*b*]; but in the present case, since the final value of Z, 1536, differs so slightly from the trial value 1538, calculated from **N**, the provisional value of **N** may stand confirmed.

(7) Fix the number of commutator segments. Lap-wound armatures may have one segment for each loop of two conductors. Modern practice is against having more loops

---

[1] If it is required that the poles should be of cast steel and circular in section, there might be some advantage in having a more elongated shape for the pole-face, for example, 21½ inches by 14 inches, which would be the size had the 67-inch core-disk been selected.

than one[1] per segment, so as to keep down the average voltage per segment. In all cases it is well to keep the number of segments high.

Example.—$Z = 1536$, or 192 conductors per pole. That makes 96 loops per pole, with an average voltage of $500 \div 96 = 5 \cdot 2$ volts per loop. As it is undesirable that the volts per segment should be unnecessarily increased, we will decide to have 768 segments in total, or 96 per pole. Arnold's rule, p. 483, prescribes as the minimum number $0 \cdot 037 \times Z \times \sqrt{C_1}$ where C_1 is the current in one conductor. In this case we have $0 \cdot 037 \times 1536 \times \sqrt{75} = 492$. Now 768 is above this number, whereas if we had tried having two loops per segment and only 384 segments we should have gone below the permissible limit. Applying as a further test rule [IX], p. 549, we find that Z/K must not exceed $2 \cdot 99$. Now this number must be an even integer, therefore the only possible ratio is 2.

(8) Fix the size of the commutator. The method is given on p. 550.

Example.—It being decided that the commutator shall have 768 segments, since each segment cannot be much less than 0·2 inches broad, the commutator will have to be at least 154 inches in periphery, or say 48 inches in diameter. It would be safer to allow 52 inches. If a brush is 0·025 inch broad; then since each brush-set now must collect 150 amperes, the net length (at 40 amperes per square inch as the density) must be 6·5; and allowing a margin, the working face should be made at least 8 inches in length. If mica 0·030 inch thick is used, the width of the copper segments at the face will be only 0·187.

(9) Next settle upon the style of armature-winding, Modern practice tends toward preserving the utmost simplicity, that is to say, it favours the lap-wound drum executed as a barrel-winding so as to have ample cooling surface, the conductors being in two layers, and with two, four or six conductors in each slot. It is true that some designers still prefer to use series-parallel windings, as they have the advantage of enabling fewer armature conductors to be used for the same

---

[1] For a case to the contrary, see Brown, Boveri & Co.'s 8-pole machine, p. 660. In motors under 50 H.P. it is usual to have more than one turn per section.

voltage, and these conductors are thicker ; and (as shown on p. 413) they give rise, in case of irregularity in the strength of the poles, to less internal heating from unequal currents in the different circuits. Some examples of designs with series-parallel windings will be found in the following machines :—

Kolben & Co.'s 10-pole, 250 kilowatt machine, p. 671.
Oerlikon Co.'s 12-pole, 350 kilowatt machine, p. 654.
Brown, Boveri & Co.'s high voltage 4-pole, p. 753.

At one time designers favoured the custom of adapting one and the same armature core so that it could be wound with the same number of conductors for 125, 250, and 500 volts provided the magnet had 4 or 8 poles: for if the 250 volts were simply a parallel (lap) winding with as many circuits as poles, the 125-volt armature would be also a duplex parallel (lap) winding (p. 367), with twice as many circuits as poles, and the 500-volt armature a series-parallel wave-winding with only half as many circuits as poles. (Compare pp. 407 to 409.) Those inexperienced in design are strongly advised to avoid wave-windings.

Example.—We will therefore choose a lap-winding; and as there are 8 poles the winding pitch will have to be selected so as to span about $\frac{1}{8}$ of the periphery. As there are 1536 conductors, the largest possible winding pitch will be $y_1 = 193, y_2 = -191$. As the pole-span is, however, only about 0·80, the lowest possible values would be $y_1 = 155, y_2 = -153$. Assuming that the conductors are placed 6 in a slot there will be 34 slots to the pole pitch, and if the maximum winding-pitch were selected, this would require the coils to span over 33 teeth, while the minimum winding-pitch would make them span over 25 teeth. As a compromise we will take it that they span over 29 teeth, in which case the winding-pitches will be $y_1 = 176, y_2 = -174$.

(10) Find armature cooling surface. The object of fixing the type of construction is that an estimate may be made of the available cooling-surface. For barrel-winding the length to which the oblique end-parts of the winding extend out will be about equal to half the pole-pitch on each side of the core-body. (Compare the various plates.)

Example.—The pole-pitch is 24·34 inches. Adding half this, or say 12½ inches, to each face of the armature core-body, which is already 15 inches long, makes the over-all length of the armature (without the commutator) 40 inches. This makes the total cylindrical cooling surface 62 × π × 40 = 7790 square inches.

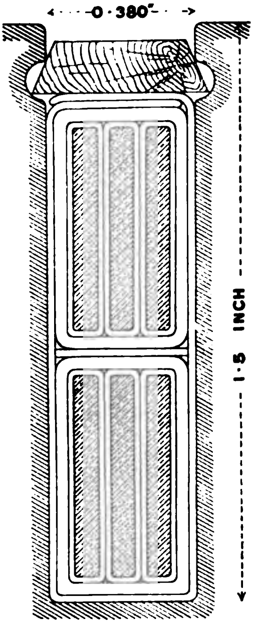
(11) Next decide upon the apportionment of the various losses. This might have been done at an earlier stage. The figures given on p. 552 will assist in apportioning the various losses. The exposed surface of the armature should have not less than 24 square inches for each kilowatt of output (see p. 187), otherwise the temperature cannot be kept within permissible limits with these percentages of loss. If on reckoning out the losses it is found that the armature surface is insufficient, the armature must be re-designed of larger size.

Example.—The efficiency is prescribed to be 93 per cent., which allows for a 7 per cent. loss. Allowing 1 per cent. for friction, 0·75 for excitation, 0·75 for commutator loss, there will remain 4½ for armature loss. Assuming the copper-loss in the armature to be 2·5 and the iron-loss to be 2·0 per cent., or in total 4½ per cent. of the output, the total watts wasted in the armature will be 4½ per cent. of 300,000 watts, or 13,500 watts. The periphery of armature being 194·75 inches and the over-all length 40 inches, the total area of the cylindrical surface is 7790 square inches. Each square inch must therefore radiate away 1·735 watts. As the surface speed is 2434 feet per minute, a reference to the curves of Fig. 99, p. 187, will show a probable rise of temperature of 45° C. On this estimate it would be preferable to reduce the copper loss by using a slightly thicker conductor.

According to the rule given above, the surface of the armature ought to be 24 times 300, *i.e.* 7200 square inches. As it has 7790 there should be ample surface.

(12) Next we may settle upon the number and dimensions of the slots. The former depends upon the type of the armature winding used and the number of commutator segments. It is almost universal now-a-days for all large machines to wind with copper strip, two layers (or sometimes four layers) deep. But whether the slot is made wide enough

to carry two, four, or six conductors depends on the conditions. Putting four or six conductors in one slot simplifies the construction and saves labour. It also saves some space, and should be adopted if there is fear of not having sufficient tooth-section for magnetic purposes. In 500-volt generators the depth of the slot varies from 1 to 2 inches or so. Assuming a proper trial value for the current-density (see p. 545) in the conductors, their proper section can be at once provisionally assigned. And, if the grouping has been chosen, the necessary area of each slot can be reckoned out by aid of a space-factor (p. 161). It must then be considered whether this leaves an adequate section for the tooth. Since the average flux-density in the air-gap is, say, 50,000 lines per square inch, and the appropriate flux-density in the teeth is 130,000 lines per square inch, one would expect the teeth to take up only five-thirteenths of the periphery. But it must be remembered that the iron of the teeth is not continuous, there being insulation, and often air-ducts, between the laminations. In the case of slots with parallel straight sides it is usual to find the width of the tops of the teeth about as great as, or slightly narrower than the width of the slots: and as the teeth slope slightly down to their roots their mean width will be less than that of the slot, and is indeed generally about three-quarters of that width. The number and arrangement of the conductors should now be readjusted to suit winding conditions.



Scale 2:1
FIG. 392.

Example.—As each conductor has to carry 75 amperes, the appropriate section at 2000 amperes per square inch will be 37,500 square mils (=0·037500 square inch). If we decide to place these 6 in a slot the total copper section per slot will be 0·225 square inch. Taking the space-factor as 0·4, we have the area of slot as 0·225 ÷ 0·4 = 0·562 square inch at least; and as there will be 256 slots and 256 teeth in a total perimeter of 194·75 inches, each slot cannot well be more than 0·38 inch wide, and each must be *at least* 1·5 inches deep. An enlarged drawing of the slot, showing to scale the arrangements of conductors and insulation, should be made, as in Fig. 392.

If the slot is lined round with hard fuller-board 12 mils thick, and if the three conductors separately taped with a taping 15 mils thick are wrapped together by a manila-paper wrapping 25 mils thick, the total breadth of insulation in the slot will be (2 × 12) + (6 × 15) + (2 × 25) = 164 mils. Deducting this from the slot-breadth 380 mils, leaves 216 mils for the total breadth of 3 copper conductors. Each of these must therefore be 72 mils thick, and as the section is required to be 0·0375 sq. inch, the width of the strip (vertical in the cut) must be 0·0375 ÷ 0·072 = 0·521 inch. As the corners of the drawn strip will be slightly rounded we may allow 0·525 inch. The contents of the slot are thus accounted for :—

Width.

3 conductors, side by side, bare	3 × 0·072 = 0·216
6 thicknesses of tape	6 × 0·015 = 0·090
2 thicknesses of slot lining	2 × 0·012 = 0·024
2 thicknesses of manila	2 × 0·025 = 0·050
Total	0·380

Depth.

2 conductors deep	2 × 0·525 = 1·050
4 thicknesses of tape	4 × 0·015 = 0·060
4 manila-paper	4 × 0·025 = 0·100
3 slot-lining	3 × 0·012 = 0·036
Wedge and packing	= 0·250
Total	1·496

(13) The internal diameter of the core may now be fixed by ascertaining the requisite radial depth of the core to give an adequate cross-section of iron below the teeth. As a trial-value one may take *either* the face-diameter of the armature divided by the number of poles, *or* a length equal to half the pole-arc. But the final adjustment of this radial depth de-

pends purely upon the permissible iron-loss, as this governs the flux-density that can be used.

Example.—$d = 62$ inches, and as there are eight poles the trial value of the radial depth is 7¾ inches; or, the pole arc being 19 inches, the half of this is 9½ inches. We may provisionally take a mean value such as 8½ inches, which, if the slots are estimated at 1½ inches deep, brings the internal diameter to 42 inches. Now the flux through the armature-core is ½ N or 6,500,000 lines. The nett length of iron from front to back being about 11·7 inches, the nett sectional area will be about 100 square inches, giving a flux-density of about 65,000, which is satisfactory (see p. 545), and will ensure that the iron-losses are not too great.

(14) Next, settle the dimensions of the air-gap by the principles laid down on p. 550.

Example.—As the slots are 0·3805 inches wide at the top, the length across the gap ought not to be less than 0·5 inch. This is sufficient as a clearance on an armature 62 inches in diameter; but by the formula [X*a*], assuming $j = 6$, we get: $l_g = 6 \times 600 \times 62 \div (8 \times 45{,}000) = 0{\cdot}62$. Formula [X*b*] gives $0{\cdot}224 \times 62 \times 14{\cdot}7 \div 768 = 0{\cdot}24$ as a minimum; but we cannot adopt this unless the pole-shoes are laminated. Formula [X*c*] gives $1536 \times 75 \div (26000 \times 8) = 0{\cdot}55$. We will take the highest of these values. This will make the field-magnet bore 63·24 inches.

(15) Fix the approximate dimensions of the magnet-pole cores. These must have sufficient cross-section to carry the full-load flux, including that which forms by leakage the stray field; and they must be long enough to receive the exciting bobbin. The flux N_m in the magnet-core will be $\nu \times N_a$; where ν is the coefficient of dispersion, N_a being taken at its full-load value. For values of ν see p. 137. A good trial-value for the length of the pole-core, if cylindrical, is to make it equal to the diameter of the section, though this may generally be reduced after the magnetic circuit calculations have been made to ascertain what provision must be made for excitation. Another rough way of obtaining a trial value for the length of the pole is to take 20 times the length of the air-gap, if the machine is to be shunt-wound, or 40 times

the length if it is to be over-compounded. The section necessary is fixed by the permissible flux-density (see p. 545).

Example.—The no-load armature flux per pole being 13,000,000 the full-load flux will need to be (for a shunt-machine or compound-wound, but not over-compounded machine) say 13,500,000. Taking the coefficient of dispersion as $\nu = 1\cdot21$ at full-load, it follows that N_m must be 16,400,000. Then taking 105,000 lines per square inch as a suitable value for the flux-density for mild steel cores, there will be required 157 square inches. Hence the pole-core, if circular, must be 14 inches in diameter; or, if square, about 12½ inches each way. Taking the other rule, if the air-gap is 0·62 inch, multiplying this by 20 gives 12·4 inches as a suitable trial-value for the length. To be certain we take 13 inches provisionally as its length.

(16) The necessary cross-section and size of the yoke may then be fixed: the section being as before fixed by the appropriate flux-density.

Example.—The yoke has to carry $\frac{1}{2} N_m$ lines, in this case 8,200,000, at full-load. Suppose it to be of cast-iron with an appropriate density not exceeding 40,000 lines per square inch. Then about 205 or 210 square inches will be needed. Being of cast-iron, a broad semi-oval section, flat in the inner face, will be appropriate, and if a breadth of 30 inches with a thickness of 9 inches at the middle be adopted, the over-all diameter of the magnet frame will be about 108 inches.

Collecting now the data so far arrived at we may tabulate the values:—

General Specification:—	
Full-load (kilowatts)	300
,, (terminal volts)	500
,, (amperes)	600
Revolutions per minute	150
Peripheral speed (feet per minute)	2430
Number of poles	8
Armature:—	
Core-disks, external diameter (inches)	62
,, internal ,, ,,	42
Length between core-heads (inches)	15
Number of slots	256
Depth of slots (inches)	1·5

Width of slots (incnes)	0·380
Pitch of slot at armature face (inch)	0·761
Depth of iron in core, under teeth (inches)	8·5
Number of conductors	1536
Arrangement	6 in slot
Style of winding	Parallel
Dimensions of each conductor, bare (inches)	0·525 × 0·072
,, ,, insulated (inches)	0·555 × 0·102
Section of each conductor (square inches)	0·0378
Mean length of one loop (inches)	103
Winding pitch in number of conductors	$y_1 = 176$; $y_2 = -174$
,, ,, teeth	33
Length of armature over all (inches)	40
Commutator:—	
Diameter (inches)	52
Number of segments	768
Active length (inches)	8
Width of segment at face (inches)	0·187
Thickness of mica insulation (inches)	0·030
Field Magnet:—	
Diameter of core (inches)	63·24
Outer diameter of yoke (inches)	108
Inner ,, ,,	90
Length of pole-core (inches)	13
Breadth of yoke ,,	30

(17) All is now provisionally ready for the commencement of the real calculation of the machine. A drawing should be sketched out to scale, using the trial-values adopted so far. This drawing will enable the designer to judge of the ultimate dimensions and appearance of the machine. From it a complete set of calculations must now be made (on the principles laid down in the preceding chapters) for (1) excitation, (2) heating,[1] (3) sparking, and (4) efficiency, as is done in the case of the typical machines discussed below. On examining the results of such calculations it is then easy to see in what manner it would be desirable to alter the design in order to fulfil more completely the specified conditions. Finally, as the outcome of such considerations, other designs ought then to be made, and worked through, differing in various ways from the first one, but fulfilling the terms of the specification. For example, if the sparking-criteria are only

---

[1] The iron losses have been calculated on pp. 100 and 105; the binding wires on p. 441.

barely fulfilled, it might be worth while to recalculate after slightly increasing the diameter of the armature: or if they are amply fulfilled, the diameter might be slightly reduced. Or if the percentage of the heat-losses in any of the parts—say the teeth—comes out either higher or lower than the amount known by experience to be advisable, then the design might be modified so as to give either a higher or a lower flux-density, as the case may be, in that part. In one respect it may be desirable to try modifications, namely, as to the grouping of the conductors in the slots. Small changes in this respect make great differences in the magnetic saturation of the teeth. This it is desirable to keep high, so that the apparent density shall attain to 130,000 or even 150,000 lines per square inch. Such densities enable smaller armatures to to be used. But to attain them without having the teeth too narrow one must put 4, 6, or 8 conductors into one slot, preferably from 0·4 to 0·6 inch wide. Further, where any doubt exists as to there being sufficient cooling surface, it may be necessary to modify and re-calculate portions of the design several times over. So soon as a design, satisfactory in these respects, has been completed, and the preliminary drawings have been made, the weights and costs can be taken out. These will afford a comparison with the weight per kilowatt, and the cost per kilowatt of other machines, and it will then be possible to consider in what way the design could be cheapened. For example, if the machine comes out too heavy, by comparison, for its prescribed output, the designer must consider whether it could not be lightened by increasing its diameter (so gaining a higher peripheral speed), and by lessening its axial length. A lighter design is frequently attained by an increase in the number of poles, though this change adds, generally, to the workmanship. The rules here given will enable the designer to design a machine that is sound from the point of view of sparking, heating, efficiency, and regulation: the selection from amongst a number of such designs of that which is of least cost is a question to be settled by reference to the market price of materials, the local cost of labour, and the running and standing costs of the factory.

OTHER PROCEDURE IN DESIGN.

It is, of course, possible to follow a different order of procedure in designing. Rothert, in an excellent paper in the *Elektrotechnische Zeitschrift* for 1901, gives the following:—Using for the estimating of the armature dimensions a constant which differs in different types of machine, but which, for a given diameter, determines the length of the core, and a formula of the type given in [I], p. 537, he then chooses the number of poles in dependence chiefly on the prescribed speed. His rule for this is that the frequency (*i.e.* the product of number of pairs of poles into revs. per second) shall lie between 17 and 20 for 500-volt machines, or between 18·5 and 22 for those over-compounded to 550 volts. From this he selects the armature dimensions so that, taking the pole-span about 72 per cent. of the pole-pitch, the pole-face shall be approximately a square, about the middle of which is centred a cylindrical steel pole. He does not calculate up the efficiency until after the main dimensions have been settled, as he finds it always to come out right, in the case of large machines, if they are only approximately correctly designed in other respects. Much more important he regards the cooling question, which can, however, be controlled by providing due ventilation. The two main factors, however, which are of vital influence in selecting dimensions are the proper magnetic saturation of the teeth, and the economy of material attained by using high current-densities in the copper. As to the former, he uses 151,000 lines per square inch (apparent) at full load. As armature current-density, he takes 1700 to 1900 amperes per square inch. Allowing a temperature-rise of 35 deg. C., and surface speeds of 1700 to 2300 feet per minute, he finds this to correspond to a waste of about 1·61 to 2·13 watts per square inch of peripheral armature surface. For the stationary coils of field-magnets he allows a current-density of 900 to 1060 amperes per square inch; and with a permissible temperature rise of 35° C., a corresponding waste of 0·77 watts per square inch of cylindrical surface.

Another order of procedure is to settle the number of poles, then the number of paths through the armature, then the appropriate size of conductor, then from the appropriate number of volts per segment of the commutator and the prescribed voltage the number of conductors. From the volts per segment the number of conductors per segment and the suitable length of core-body can be determined, and on selecting a suitable grouping in the slots and an appropriate insulation, the size of slot can be found. The permissible losses may be assigned at any stage, and from those allowable in the teeth the size of tooth may then be determined. From this and the size and number of slots the diameter of the armature becomes known. The field-magnet calculation follows as before.

Dr. Max Corsepius in his book on construction, *Leitfaden zur Konstruktion von Dynamomaschinen* (3rd edition, Berlin, 1903), has given yet another procedure in which he starts from the arrangement of the conductors in the slot and the slot-pitch, and gives formulæ for deducing the size of the diameter from these and the speed, voltage and number of poles.

REFINEMENTS IN DESIGN.

It is possible in almost every one of the preceding matters of calculation to enter into greater refinements, and different designers of experience have their own methods of working out details. It must suffice to indicate a few of such refinements.

Coefficient of Magnetic Dispersion.—As this is not a constant, but increases with the load, some makers work it out with great elaboration for different loads. For continuous-current machines, this is generally superfluous, but for alternators, in which the drop of voltage on an inductive load depends mainly on the dispersion, it is all-important.

Equivalent Pole-arc.—It has been assumed as sufficient hitherto that the pole-arc, or effective span of the pole, can be expressed as a simple fraction of the pole-pitch, both pole-span and pole-pitch being measured at the armature face. The ratio $\psi = \frac{\text{pole-span}}{\text{pole-pitch}}$, varying from 0·6 to 0·8 in different machines, assumes that the pole-span is a definite length. But in order to procure a suitable fringe of field for good commutation, the pole-tips are usually shaped away, as described on p. 269, and the extreme span from tip to tip is therefore really no exact measure of the effective width of the field. The effective pole-span can, however, be ascertained by a preliminary process. It is first necessary to find the distribution of the field at no-load. This can be done in the following way. Let a drawing be made to scale of one pole, and of the armature outline at the proper width of gap below it. Then, beginning at the middle point under the pole, let the pole-pitch be divided into any number of equal parts right and left, for example, into 18 parts, 9 on each side. Then, judging by experience as to the probable form of the magnetic lines as they cross the gap, let a number of representative lines be drawn, one for each "part," to meet the pole, as in Fig. 393. Then from the drawing estimate the lengths of these lines: those near the middle of the pole-face will all be of equal length. Then set out, as ordinates, equally spaced out, from a convenient base line, a number of lines such that the length of each is inversely proportional to the length across the gap at the corresponding part. These ordinates being joined in a curve it will represent (on the assumption that the length of the pole-face from front to back is the same at every part) the distribution of the intensity of the field since the flux-density (undisturbed by reaction) is inversely proportional to the length of path across the gap. If the length of pole-face from front to back is not uniform, but varies, as for instance when the pole corners are shaped polygonally as in Fig. 153*b*, the height of the corresponding ordinates must be proportionally reduced. Having thus obtained a corrected curve, as in Fig. 393, the next step is to square it off as shown, so that the rectangular area *a b c d* shall be equal to the area under the curve. Then the length *a d* represents to scale the reduced or *equivalent pole-span*, and the true value of ψ is the ratio of *this* to the pole-pitch, which is the length along the base-line from "0" to "0."

We have seen, in the deduction of the rational formulæ for output in relation to size, how important it is that this ratio should be as high as possible. But there are two considerations which tend to lower it. In order to obtain a proper commuting fringe the pole-tips must be rounded or chamfered

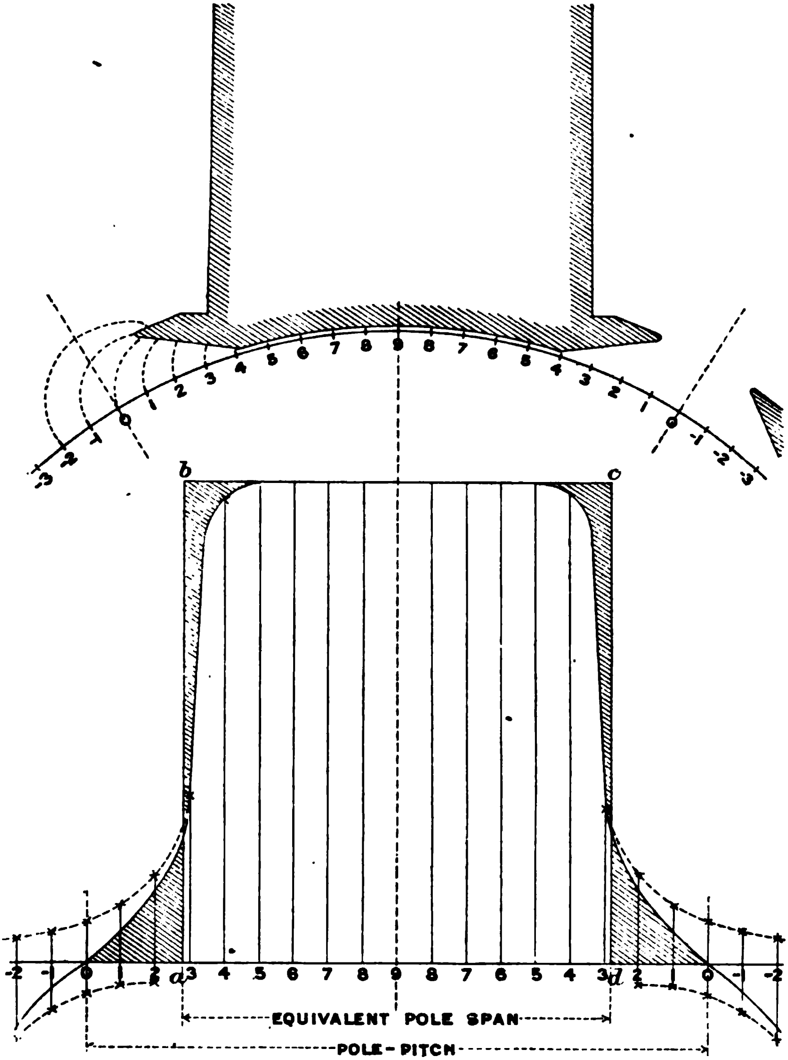


FIG. 393.—GRAPHIC CALCULATION OF FIELD DISTRIBUTION.

away, and this clearly tends to shorten the equivalent pole-span. Again, if the pole-tips are brought very near together there will be a considerable magnetic leakage. This, in continuous current machines, is no great harm. Further, in Fig. 393 only one pole was drawn, and its individual field extends right and left beyond the neutral points of the field marked "o" as shown by the dotted line; so that in estimating the distribution of the field, one must take into account the effect of the neighbouring poles which will bring the curve down to a zero at "o."

Again, if the armature has wide open slots, the presence of these slots may perturb the distribution of the field; for which reason some designers go even more minutely into the matter and plot two curves; one for the distribution when a slot is opposite "o," and one for that when a tooth is opposite "o."

Commuting Fringe.—We have seen on pp. 262 to 269, what pains designers have taken to ensure that at full-load there shall be an adequate commuting field under the hindward pole-tip. If by a modification of the preceding process the curve of distribution is drawn for the field as distorted at full-load it will be seen that the breadth and slope of the commuting fringe is altered. Now, for good commutation it is not unimportant that this part of the field should be not only adequately strong, but that it should have a sufficient breadth, and that its slope should give the requisite electromotive-force at each instant. If the potential under the brush is to be uniform all along under the brush, the intensity of the field in the fringe at the point corresponding to the beginning of the commutation must not be too strong, otherwise the potential will fall under the middle of the brush. Neither must it be too weak, otherwise the potential will rise. Neither must the corresponding field at the end of the commutation be too strong, otherwise the potential will fall, and there will be over-commutation of the current in the loop. It is, therefore, desirable that the pole-tips should be so shaped that the (corrected) curve of distribution shall have at the neutral points "o," a well-defined and not too steep slope extending to a sufficient distance from "o" toward the pole.

A simple mode of attempting to realize this is adopted by the Oerlikon Co., who construct their laminated pole-cores out of stampings assembled in blocks about an inch thick. The tips of the successive blocks are cut away to different lengths, as represented in Fig. 394. Another device used for securing a fringe, and at the same time saturating the tips, is shown in Fig. 395.

Length of Armature Conductors. — Various simple rules have been given by designers for estimating the length of 1 loop of an armature conductor for different styles of winding. For barrel-winding a simple approximation is that the length (in inches) of copper in 1 loop is equal to $3 + 2l + 7d \div p$. Thus for an 8-pole machine with $d = 62$ and $l = 15$ the approximate length round one loop will be 93 inches.

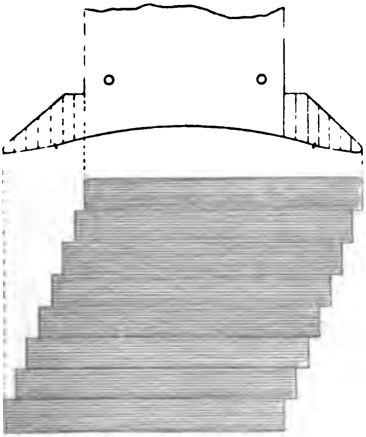


FIG. 394.—SHAPED POLE-TIPS.

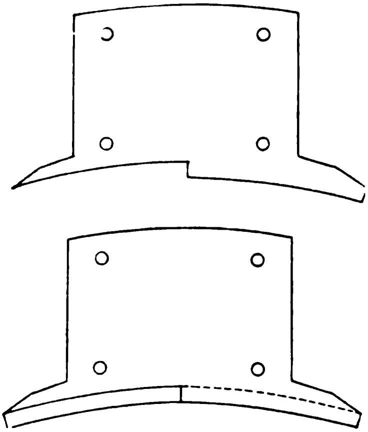


FIG. 395.—SHAPED POLE-STAMPINGS.

Shunt and Compound Machines.—Machines intended to be used as over-compounded generators must be designed a little more liberally than those designed for same speed and voltage as shunt machines, so as to allow for the increase of magnetic flux and additional excitation losses at full-load; or, what comes to the same thing, if of equal dimensions, they must for the same speed be rated as of, say, from 5 to 7 per cent. lower output; or, if rated at the same output, their speed must be increased from 5 to 7 per cent.

WEIGHTS AND COSTS.

Any design in which either of the flux-densities in the iron or the current-densities in the copper are needlessly low, will necessarily be unduly bulky, and, therefore, unduly heavy and costly. If the magnetic and electric densities are too high, the permissible rise of temperature may be exceeded or the total losses may be too great. A high efficiency may be attained by keeping densities low; yet a lighter machine with an equally high efficiency may be obtained with high densities and a less weight of material, provided proper cooling arrangements are made. All insulation takes space and increases the total bulk and therefore the weight and cost of the machine. It is, therefore, from the point of view of economy of metal to keep insulation as thin as is practicable, and by the use of mica and the avoidance of using round wires, to keep the space-factors as high as possible. The practice of putting several conductors into one slot effects a notable saving in the size of the armature, and enables the flux-density in the teeth to be raised to a point otherwise unattainable.

As the cost of material varies and the price of labour also varies from one country to another, and even between different districts in the same country, it follows that the design which can be most cheaply produced in one factory to fulfil given conditions will differ from that which can in another factory be produced most cheaply.

A few general rules may, however, be laid down.

As to weights, machines with a low peripheral speed always weigh more than those of equal output with a high speed; and those with cast-iron yokes more than those with steel yokes. The armature weight (apart from the shaft) ought to be approximately proportional to the kilowatts if equal peripheral speeds are attained. For armatures over 40 inches in diameter the weight and cost are closely proportional to the product d^2l; for those under this size, the weight and cost vary somewhat with the ratio of d to l. The ratio of copper to iron is less in machines with a high ratio of d to l, than in those with a low ratio of d to l, and of equal speed and output. The total factory costs of dynamos are not proportional to their outputs, because high-speed machines cost less than low-speed machines of equal output. Neither is the cost proportional to the output divided by the speed. Even in a given series of machines of different sizes manufactured in the same works it is not proportional to the product d^2l. A simple relation can however be stated in the form:—

$$\text{cost} = \text{A} + \text{B}\,(d^2l).$$

According to Mr. E. K. Scott[1] the constants A and B giving the cost in £ sterling, in a certain English works, were 140 and 0·018 respectively. For example, a machine having $d = 62''$, $l = 15''$, would cost £1293 in the factory. Its output at any given speed would obviously be limited by heating or sparking, or both. Scott has given the following example of the allotment of costs of material for a machine of about the above size.

Material.	*Percentage of Total Cost of Material.*	
Armature conductors	6	31 per cent. of copper.
Field-magnet coils	19	
Commutator segments	6	
Armature core stampings	12	39 per cent. of iron.
Magnet pole cores	7	
Yoke	20	
Insulating materials	8	
Miscellaneous	22	
	100	

Prof. E. Wilson[2] has discussed the ratio of price to output, chiefly in relation to bipolar machines, and Mr. H. A. Mavor[3] has shown how the watts per revolution and the corresponding cost are related to the proportions of the armature. More recently[4] Mr. Mavor has discussed the best speed for a motor of given size under given heating limits, and the best depth of slot.

Hobart has considered[5] the problem of designing series of generators of standard patterns to cheapen manufacture. His designs favour a high surface speed, large commutator, and high current-density in the armature, from 2340 to 2520 amperes per square inch. He has also discussed the cost of the "nett effective material," that is to say, the iron and copper which are magnetically and electrically employed, to the exclusion of bed-plates, shafts, spiders, bearings and brush gear. He gives, for machines from 80 to 150 kilowatts, a mean value of the cost of "nett effective material" as 16·3 shillings per kilowatt. The total factory cost per kilowatt will however decrease for larger capacities, since, for machines of larger capacity the "nett effective material" constitutes a larger percentage of the total cost. With higher speeds, the cost of a machine of given capacity goes down, varying about inversely as the square root of the speed. Low-voltage machines require a larger, and, therefore, a more costly commutator than high-voltage machines of the same rated kilowatts at the same speeds.

---

[1] *Journ. Inst. Elec. Engineers,* xxxii. 400, 1903.

[2] *Ibid.*, xxvi. 160, 1897.

[3] *Ibid.*

[4] *Ibid.*, xxxii. 473, 1902.

[5] *Ibid.*, xxxi. 170, 1901.

The actual costs of materials at the present date may be stated somewhat as follows:—Copper, whether for armature, commutator or field-magnet coils, 10*d.* per pound; armature stampings 1¾*d.* per pound; cast-steel or wrought-iron for pole-cores and yoke, 2¼*d.* per pound; and cast-iron 1½*d.* per pound.

Most of the foregoing considerations are stated with respect to machines of large and of moderate sizes. The cost of small machines—say under 5 kilowatts—is relatively higher on account of the larger proportion borne by workmanship; so that their cost is mainly a question of the degree to which the factory has been organized for turning them out in quantities of standard sizes. For a 50 kilowatt machine the sale price stands at about tenpence per pound of total weight. The price of larger machines decreases to about sixpence per pound when machines of 1000 kilowatts are reached. But for very small machines the price rises to as much as three shillings per pound.

Hobart in the *Electrician*, li. 840, Sept. 11, 1903, has shown that for a series of machines of similar type (for instance, of 500-volt machines with barrel-wound armatures), the factory cost is with remarkable accuracy proportional to the product of the armature diameter into the over-all length of the armature, taken over the end-connexions. It is therefore simply proportional to the cylindrical surface of the armature. He proposes that the term "specific output" shall be defined as the ratio of full-load watts to the product of armature surface and rated speed. Or, using the symbol L for the over-all length and Q for the "specific output" we have:—

$$Q = \frac{W}{\pi d L \times r.p.m.};$$

from which we may deduce a formula useful in preliminary design,

$$dL = \frac{W}{\pi \times Q \times r.p.m.}.$$

Q is, in fact, the number of watts per square inch of armature surface, at unit speed.

The values of Q for some of the machines described below are:—Oerlikon 500 kw., p. 654, 0·426; Scott and Mountain 150 kw., p. 582, 0·136; General Elect. Co. 550 kw., p. 678, 0·5; Hobart 1000 kw., p. 632, 0·81.

SPECIFIC UTILIZATION OF MATERIAL.

Good design utilizes to the utmost the materials employed. The copper should be made to carry the largest current, the iron to receive the greatest density of flux, consistent with efficiency and coolness, and the movement of the copper across the magnetic field should take place at the highest speed consistent with mechanical safety.

The Active Belt.—Mavor has introduced[1] the conception of the "active belt," meaning by this term the entire mass of the armature periphery down to the roots of the teeth, consisting of iron, copper, and insulation. It is in this active belt that the whole inductive generation takes place, and on this active belt that the mechanical forces are exerted. Mr. Mavor found the number of ergs per second per cubic centimetre at unit velocity in unit field to be about 5. But the work done per line in moving a current across a field is simply proportional to the current: so that Mr. Mavor's figure is a measure of the current-density in the gross section of the active belt.

---

[1] *Journ. Inst. Elec. Engineers*, xxxi. 218, 1901.

We may extend still further this conception of a belt of active material, and may consider not only the mean number of amperes that traverse each square inch of it parallel to the shaft, but also the mean number of magnetic lines that traverse each square inch of it radially, and the speed with which it moves forward tangentially. Let us consider the number of watts generated per cubic inch of the active belt. If d be the diameter, l the length of the core-body, and s the depth of the slot (or length of the tooth), the total volume of the active belt will be $\pi d l s$. Hence:—

$$\text{Watts per cubic inch} = \frac{\text{E C}}{\pi d l s}.$$

Now, writing for E the value $n \text{Z} \text{N} p \div c\, 10^8$; and remembering that $n = v \div \pi d$, where v is the peripheral velocity in inches per second, we have:—

$$\text{Watts per cubic inch} = \frac{\text{Z C N} p v}{c \pi^2 d^2 l s . 10^8}.$$

This we may decompose into three factors, thus:—

$$\text{Watts per cubic inch} = \frac{\text{Z C}}{\pi c d s} \cdot \frac{\text{N} p}{\pi d l} \cdot \frac{v}{10^8}.$$

These three factors we may severally write:—

$\text{Z C} \div \pi c d s = a =$ gross current-density per square inch in active belt.

$\text{N} p \div \pi d l \;= \beta =$ gross magnetic density per square inch in active belt.

$v \div 10^8 \qquad = \gamma =$ a quantity proportional to the peripheral velocity.

If, then, we take out these three factors a, β, and γ for any particular machine, we have at once a means of comparison between its design and that of other machines in respect of the specific utilization of materials. Some makers manage to crowd many amperes through the copper: in their machines a will be large. Other makers contrive to have a high average flux-density in the belt: in their machines β will be large. Others drive their machines with a high surface speed, and so increase the specific output of a given quantity of active material. Owing to the conditions that are necessitated by sparkless commutation a cannot be very high unless β is high also, though β may be high without a being so. And γ may be high or low, quite independently of a or β.

The author has therefore made a detailed examination of more than fifty modern generators, including the machines mentioned in this book, to ascertain the values of these three factors of specific utilization. The values of a for machines of the type principally dealt with lie mostly between 300 and 460, a few being outside these limits. The values of β lie mostly between 30,000 and 45,000, the extreme values being 22,000 and 58,000. The values of γ lie mostly between 0·000004 and 0·000009; but in a few cases exceed the latter figure. The watts per cubic inch of active belt run from about 45 to 120; but in one case go down to 15, and another case, Hobart's 1600 kw. generator, reach 162. Smooth-core machines are not included in these calculations, nor arc-lighting machines, nor magneto machines, nor any small designs. See the Table on p. 701.

Schedules for Designing.—On the next page begins a 4-page schedule, which will be found of great assistance both in the analysis of existing designs, and in the designing of new machines. Mr. Hobart has published in the *Electrical Review* of December 5 and 12 of 1902, vol. li., p. 928 and p. 975, a much more elaborate set of specification forms.

SCHEDULE FOR CONTINUOUS CURRENT DYNAMO DESIGN.

Type of Machine____; ____Poles; ____Kw.; ____Revs. p. min.;
____Volts; ____Amperes.

*Design calculated by*____________________

*Machine constructed by*____________________

*In operation at*____________________

*Type*____________________

*Weight complete*____________________

*Voltage, No Load*__________*Full Load*__________

*Over compounding*__________*Volts,*____%

COMMERCIAL TEST.

Load.	Revs. per minute.	Volts.	Current.		Output Kw.	Losses—Watts.					Efficiency.
			Arm.	Shunt.		Arm Copper	Arm. Iron.	Excitation.	Friction.	Total.	
No Load ...											
¼ Load ...											
½ Load ...											
¾ Load ...											
Full Load...											
1¼ Load ...											

Test made after ____ hours' continuous run; Armature Current ____ amps.; Shunt Current ____ amps.; E.M.F.____ volts. Resistance in shunt____ohms. Measured Resistance of Shunt Winding: cold (____°C.) ____ohms.; hot (____°C)____ohms.

Remarks:

Date of test ____ Test made by ____

DIMENSIONS.

ARMATURE.

diameter at face
periphery
pole pitch at armature face
length between core heads
diameter × by core length ÷ kilowatts
thickness of core sheets
number of ventilating ducts
width of each duct
effective length of core
radial depth core body
internal diameter core
number of slots
depth of slot
width ,,
,, ,, at armature face
minimum width of tooth
width of tooth at armature face
total number of face conductors
number of circuits
style of winding
number of conductors in series between + and —
size or section of conductor (bare)
size or section of conductor insulated
mean length of conductor per turn
pitch of winding (front and back)
,, ,, number of teeth
arrangement of conductors in slot
copper section ÷ slot section (space factor)
length of active conductor per volt
total insulation between conductor and core

GAP.

length at centre from iron to iron
diameter of **bore of field**

POLE PIECE.

length parallel to shaft
length of pole arc
average pole arc ÷ pitch

MAGNET CORE.

length radially
length parallel to shaft
width or diameter

BOBBIN.

length over all
thickness of insulation on flanges
,, ,, ,, body
length of shunt winding space, excluding insulation
size of shunt wire
mean length of one turn
compound conductor, size or section of

YOKE.

outside diameter
inside diameter
thickness
length parallel to shaft

COMMUTATOR.

diameter
length of segment over all
area of cylindrical surface
active length of segment
number of segments
width of segments
useful depth of segment
thickness of insulation between segments
peripheral speed, ft. per min.

COMMUTATOR BRUSHES.

number of sets
number in one set
length side by side
width (peripheral) of brush in inches
,, ,, ,, in segments
size of contact face
total area of contact, one polarity

ELECTRICAL.

ARMATURE.

E.M.F. per circuit, no load
,, ,, full load
type of winding
number of turns per segment
winding formula
amperes per circuit of winding
amperes per square inch in conductor
C R drop (lost volts) in armature
ohms brush to brush (at 60° C.)
amperes per square inch of active peripheral belt

COMMUTATOR.

average volts between bars
reversal density ÷ pole face density
amperes per square inch of brush contact
C R drop due to brush contact

FIELD COILS.

type
number of turns in series per bobbin
number of bobbins in series
mean length of one turn
total resistance (at 60° C.)
amperes, full load
amperes, no load (shunt excitation)
amperes, per square inch, full load
rheostat resistance
C R drop (lost volts) in rheostat

COMPOUND WINDING.

arrangement of
number of turns in series per bobbin
mean length of one turn
total resistance (at 60° C.)
amperes full load
amperes per square inch, full load

REACTIONS.

ARMATURE.

ampere conductors, per pole
,, ,, beneath pole
,, ,, between poles
,, ,, per inch periphery, full load
,, turns, gap and teeth ÷ beneath pole
density in gap under backward pole-horn at 1¼ load

FIELD.

ampere turns, no load, no load volts
,, ,, ,, full ,,
% added for armature reaction
total ampere turns, full load
ampere turns shunt coil, full load
,, ,, compound coil, full load
,, ,, total ,, ,,
inherent regulation %

SCHEDULE OF CALCULATIONS FOR WINDING OF FIELD MAGNETS.

Flux at no-load .... lines ; Flux at full-load .... lines. Co-efficient of allowance for dispersion ....

		Flux from one pole (megalines).	Sectional Area.	Flux Density.	Mean magnetic length.	Ampere-turns per unit length (from curve).	Ampere-turns needed.
At No-Load.	Armature body						
	Teeth . . .						
	Gap . . .						
	Pole Core . .						
	Yoke . . .						

Total ampere-turns needed at no-load =

At Full-Load.	Armature body						
	Teeth . . .						
	Gap . . .						
	Pole Core . .						
	Yoke . . .						

Total ampere-turns needed at full load . . . =

Add ampere-turns needed to compensate reaction =

Deduct ampere-turns at no-load . . . . . . =

Difference . . . =

CALCULATION OF SHUNT BOBBIN.

Assuming suitable current density amperes per square inch of copper, the appropriate wire will be No. ...... S.W.G. This wire has .... diameter bare, or .... diameter covered. The number of shunt-turns being .... these will occupy square inches of winding space on the bobbin. The available length of winding space on the bobbin being ...... inches, the depth occupied will therefore be ...... inches. Minimum circumference of winding is .... inches ; maximum circumference is .... inches ; hence mean length of one turn is .... inches = ... feet. Resistance of one bobbin ...... ohms (at 60° C). Watts lost in one bobbin .... Weight of .... feet, in lbs. .... Assuming total watts lost in all shunt coils to be 0·75 per cent. of total out-put (kilowatts) of machine, this limits loss per bobbin to .... watts. Taking this value, weight of copper per bobbin may be found by following formula :—

$$\text{Pounds of copper per bobbin} = \frac{31 \times (\text{ampere-turns} \times \text{mean length of one turn in feet})^2}{\text{watts per bobbin at } 20^\circ\text{C} \times 10^6}.$$

Bobbins being .... inches long, with .... inches external diameter, the cooling surface is .... square inches ; watts per square inch .... ; hence probable temperature rise .... deg. C. N.B.—Total radiating surface of all the bobbins ought to be about 15 times the total kilowatts of out-put. Probable temperature rise 75° C. per watt per square inch.

CALCULATION OF SERIES WINDING.

Assuming current density .... amperes per square inch of copper, the needful cross-section will be .... square inches, and may be provided by strip copper of thickness .... inch (= No. .... S.W.G.) and .... inches broad. Mean length of one turn .... inches ; total length of strip required .... inches = ... feet for one pole, or .... feet in total.

GAP CO-EFFICIENTS.

N.B.—In calculating air gaps the number of ampere turns needed, per inch length across air gap, is obtained by multiplying by 0·3133 the flux density if expressed in lines per square inch or the number of ampere turns needed, per centimetre length of gap, is obtained by multiplying by 0·796 the flux density if expressed in lines per square centimetre.

= Ampere-turns of shunt-winding. Shunt current, taken at—— per cent. of full-load current, ——amperes ; hence Number of Shunt-turns per pole = ——.

COMPENSATING REACTION.

The number of demagnetizing ampere-turns per pole may be approximately calculated by reckoning the number of conductors in the region between two adjacent pole-horns and multiplying this number by the number of amperes carried by each conductor.

= Ampere turns to be provided by compound winding. Full-load current is ———— amperes ; hence Number of Series turns per pole = ———.

REMARKS.

TEMPERATURE TEST.

Conditions of Test.					Degrees Rise—Centigrade.								
Duration.	Volts.	Armature Current.	Shunt Current.	Temp. Room.	Armature.		Shunt.		Series.		Comm'r.	Bearings.	Frame.
					Ther.	Res.	Ther.	Res.	Ther.	Res.			
After hours run													
,, ,,													
,, ,,													
,, ,,													

Remarks ______________________________

Date of test ____________ *Test made by* ____________

WEIGHTS AND COSTS.

Machine Parts.	Material.	Weight.	Cost of Finished Product.			
			Per Pound.	Total.	Per Kw.	Per 100 Revs.
Yoke						
Poles						
Armature Core ...						
Armature Copper ...						
Commutator ...						
Shunt Coil						
Series Coil						
Armature Spider ...						
Armature Shaft ...						
Brush Gear, &c. ...						
Bedplate & Bearings						
	Totals					

N.B.—Copies of this four-page Schedule, printed large, on pages 16 inches by 10 inches size, can be had in quantity from the Publishers.

CHAPTER XIX.

ANALYSIS OF DYNAMO DESIGN.

We now proceed to analyse the designs of some machines of different types, as examples of the foregoing principles and methods.

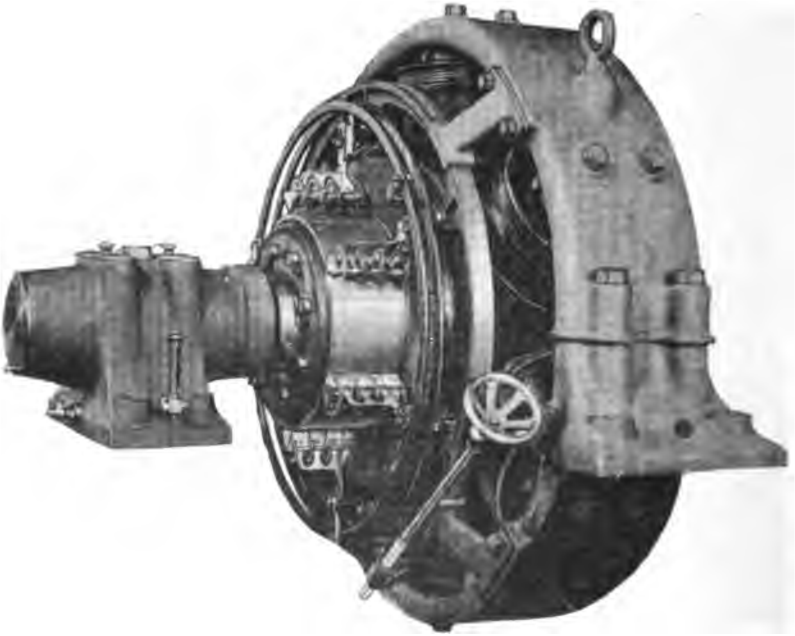


Fig. 396.

Example I.—SHUNT-WOUND MULTIPOLAR MACHINE WITH SLOTTED DRUM ARMATURE.

Built by Messrs. Ernest Scott and Mountain.

M.P. 6—150—450—250 volts—600 amps.

(Shown in Figs. 396 & 427, and Plate V. For description, see p. 665.)

The leading dimensions and particulars as obtained from the drawings are given in the schedule form below.

GENERAL SPECIFICATION.

Full load (kilowatts)	150
,, (terminal volts)	250
,, (amperes)	600
Revolutions per minute	450
Peripheral speed (feet per minute)	3885
Number of poles	6
Nature of load	Lighting

DIMENSIONS.

Armature:—

Core disks, external diameter (inches)	33
,, internal ,, ,,	18
Number of slots	124
Depth of slot (inch)	1·625
Width ,, ,,	0·4
Pitch of slot at armature face (inch)	0·840
,, ,, average (inch)	0·796
Depth of iron in core, under teeth (inches)	5·875
Gross length of core (inches)	11
Iron ,, ,, ,,	9
Diameter of finished armature (inches)	33
Number of conductors	496
Arrangement	4 in slot
Style of winding	parallel
Dimensions of each conductor, bare (inches)	0·7 × 0·11
,, ,, ,, insulated (inches)	0·73 × 0·14
Section of each conductor (square inch)	0·077
Mean length, one armature turn (inches)	66

Field-Magnets:—

Diameter of bore (inches)	33·625
Polar angle (degrees)	43
Turns per pair of poles	3602
Mean length of one turn (inches)	43
Diameter of wire, bare (inch)	0·09
Section of wire (square inch)	0·0050
Shunt current (amperes)	4·10

Commutator:—

Diameter (inches)	21
Number of segments	248
Active length (inches)	7·5

An inspection of the drawings shows that the magnet cores of steel are of circular section, bolted on to the yoke, the pole pieces being in one piece with the magnet cores.

The field-frame is cast in two pieces and bolted together. All the field-bobbins are connected in series. The armature slots are straight, and of the dimensions given above. There are two ventilating apertures, each $\frac{3}{8}$ inch wide, and the core disks are insulated with varnish, deducting altogether 18 per cent. from the gross section.

The armature winding has six parallel circuits, and six sets of brushes at 60° apart.

We will first construct the saturation curve of the machine. We have :—

$$E = n \times Z \times N_a \div 10^8,$$

or

$$E = \frac{450}{60} \times 496 \times N_a \div 10^8;$$

$$E = 0{\cdot}00000372\ N_a.$$

The dispersion coefficient of this machine is $\nu = 1{\cdot}17$. Hence we have :—

E	N_a	N_m
300	8,100,000	9,480,000
280	7,530,000	8,800,000
260	7,000,000	8,200,000
230	6,180,000	7,230,000
200	5,400,000	6,320,000

From the drawings we obtain :—

Length of mean magnetic path in	magnet yoke (inches)	26
,, ,,	two magnet cores (inches)	28
,, ,,	armature core ,,	15
,, ,,	two teeth ,,	3·250
,, ,,	two air-gaps (inch)	0·625

And for the magnetic areas :—

For the yoke (square inches)	= 44
,, magnet cores (square inches)	= 78·5
,, armature body ,,	= 53·0

The polar angle being 43°, we have for the number of teeth under one pole

$$\frac{124 \times 43}{360} = 14{\cdot}7.$$

Owing to the high flux-densities in the teeth the flux will spread considerably, so we will assume 16 teeth as the number under 1 pole.

The pitch of the slots at armature face is 0·84 inch, and hence the width of the tooth = 0·840 − 0·400 = 0·44.

Consequently the area of the teeth under each pole may be taken as:—

$$16 \times 0{\cdot}44 \times 9 = 64 \text{ square inches.}$$

The air-gap area will be taken as the mean of the tooth area and pole-face area, or

$$\frac{140 + 64}{2} = 102 \text{ square inches.}$$

We have now all the data for constructing the saturation curve and no-load characteristic. It will be sufficient here to work out two points on the curve, as the method is the same for them all.

Taking the point E = 260 and E = 230 as examples, we obtain the two tabulations given below.

The values of ampere-turns per inch, δ, have been taken from the magnetization curves given in Plate I., though it is quite probable that the actual brands of cast-steel and of iron stampings used by the makers had slightly different values.

The value for the air-gap might be obtained by the use of the gap-coefficient 0·3133, as explained on pp. 92 and 143.

$E = 230$. $N_a = 6{,}180{,}000$. $N_m = 7{,}230{,}000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux Density.	Value of δ from Curve.	Ampere Turns.
		in.	sq. in.			
Yoke	cast steel	26	2 × 44	82,300	23	597
Two magnet cores	cast steel	28	78·5	92,100	32	895
Two air-gaps	air	0·625	102	60,700	192 (per $\frac{1}{100}$ inch)	11,887
Two teeth	iron stampings	3·250	64	97,000	23	75
Armature core	iron stampings	15	2 × 53	58,400	2·75	41
					Total ampere-turns per pair of poles	13,495

$E = 260$. $N_a = 7,000,000$. $N_m = 8,200,000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux Density.	Value of δ from Curve.	Ampere-Turns.
		in.	sq. in.			
Yoke	cast steel	26	2 × 44	93,200	34	884
Two magnet cores	cast steel	28	78·5	104,300	60	1,680
Two air-gaps	air	0·625	102	68,600	215 (per $\frac{1}{100}$ inch)	13,430
Two teeth	iron stampings	3·250	64	109,000	107	348
Armature core	iron stampings	15	2 × 53	66,000	4	60
					Total ampere-turns per pair of poles	16,402

In the same way we calculate other points of the curve obtaining :—

When

$E = 200$, necessary ampere-turns $= 11,251$
$E = 280$ „ „ $= 20,298$
$E = 300$ „ „ $= 25,915$

By plotting the curve connecting these five points we obtain the working part of the saturation curve, as shown in Fig. 397. We have then for $E = 250$ volts ;

Necessary ampere-turns at no-load $= X_1 = 15,300$.

We will now proceed to find the necessary ampere-turns at full-load. These will be greater than those required at no-load by an amount depending upon :—

1. The value of the full-load lost volts.
2. Amount of armature demagnetization.
3. „ „ distortion.

Now the resistance of the armature including brush-leads and carbon brushes is 0·0081 ohm brush-to-brush at the working temperature.

The resistance of the series coils is 0·00083 ohm.

Hence the total resistance of the main current circuit in the machine is (0·0081 + 0·00083) = 0·00893 ohm.

The full-load drop is therefore :—

$$e = 600 \times 0{\cdot}00893 = 5{\cdot}3 \text{ volts.}$$

Now the terminal voltage of the machine at full-load is 250. Hence the armature must generate at full-load 250 + 5·3 = 255·3 volts.

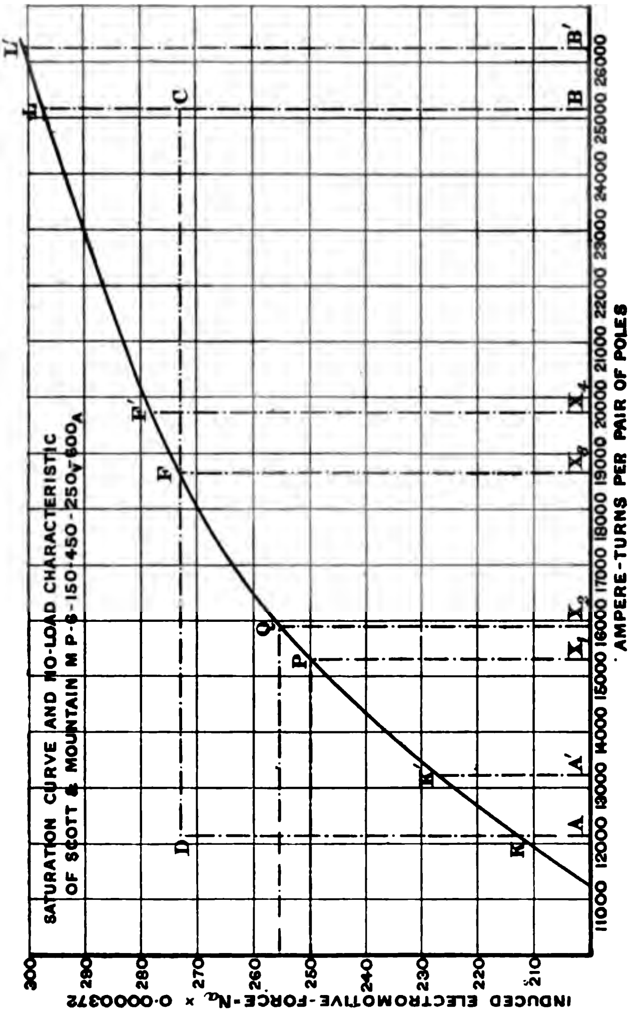


FIG. 397.—PREDETERMINATION OF SATURATION CURVE OF SCOTT AND MOUNTAIN 6-POLE, 150 KW. DYNAMO.

Finding this point on the scale of ordinates of the curve and projecting it across we find the point X_2 on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at full-load if armature reaction were entirely absent. This makes $X_2 = 15{,}900$.

Now, the number of slots lying between the pole-tips is

$$\frac{60 - 43}{360} \times 124 = 5{\cdot}8$$

and in each slot there are four conductors carrying 100 amperes at full-load. Hence the demagnetizing turns of the armature at full-load, and upon the assumption that the brushes are moved right under the pole-tips, are

$$5{\cdot}8 \times 4 \times 100 = 2320.$$

Multiplying this number by ν, the necessary compensating ampere-turns per pair of poles are therefore

$$2320 \times 1{\cdot}17 = 2715.$$

Adding, then, these ampere-turns to X_2 we find $X_3 = 18{,}615$ as the ampere-turns necessary at full-load, assuming that there were no drop of pressure due to the diminished permeability of the teeth at the forward pole-horn, due to distortion of the flux. But this is not the case. We must therefore allow for this as explained on p. 527.

For this we have :—

$$\left.\begin{array}{r}\text{Ampere-turns}\\ \text{under one pair poles}\end{array}\right\} = \frac{47}{360} \times 124 \times 4 \times 100$$

$$= 6500.$$

We set off, therefore, 6500 ampere-turns on each side of the point X_3 upon the scale of abscissæ, and obtain thus the points A and B, which represent the hindward and forward pole-horns respectively. If distortion of the main flux were absent, the latter would be proportional to the area A B C D. But as this is not so, it is proportional to the smaller area A B L K. In order to make this area equal to that of the rectangle, we must shift the point F higher up the curve to the position F′, so that

$$\text{Area } A'B'L'K' = \text{area } ABCD.$$

In this manner we obtain the point X_4 as the necessary ampere-turns at full-load.

Their value is

$$X_4 = 19{,}700.$$

Comparing our calculated results with the actual values of the running machine, we have :—

Output.	Calculated Values.	Actual Values.
At no-load . .	15,300	14,800
At full-load .	19,700	17,800

The discrepancy between the values calculated from the drawings and the values found by the makers, is probably due to the quality of iron actually used being better than that assumed in the calculations.

The full-load excitation is made up as follows :—

Shunt-turns per pair of poles, 3602 carrying 4·10 amperes.

Series-turns per pair of poles 5 carrying 600 amperes.

Total ampere-turns per pair of poles :—

$$3602 \times 4{\cdot}1 = 14{,}800 \text{ shunt ampere-turns.}$$
$$5 \times 600 = 3{,}000 \text{ series ampere-turns.}$$
$$\therefore \text{ Total ampere-turns } = \underline{\overline{17{,}800}}$$

LOSSES.

1. *Copper Loss* :—

Armature.

$$w_{ca} = 600 \times 600 \times 0{\cdot}004$$
$$= 1440 \text{ watts.}$$

Series Coils.

$$w_{cc} = 600 \times 600 \times 0{\cdot}00083\,;$$
$$= 298 \text{ watts}\,;$$
$$\therefore\ w_c = 1738 \text{ ,,}$$

2. *Iron Loss.*—The number of cubic inches of iron in the teeth is :—

$$1{\cdot}625 \times 0{\cdot}396 \times 9 \times 124 = 720 \text{ cubic inches.}$$

The frequency of reversal of magnetism is :—

$$3 \times 450 \div 60 = 22{\cdot}5 \text{ cycles per second.}$$

At full-load the flux-density is 130,000 lines per square inch. Reference to the curve (p. 103) shows that at 130,000 lines per square inch, and taking η (the hysteretic constant) as 0·003, which is a probable value for armature stampings, the hysteresis loss will be about 0·038 watt per cubic inch of iron at 1 cycle per second. Hence the hysteresis loss in the teeth is :—

$$720 \times 0{\cdot}038 \times 22{\cdot}6 = 620 \text{ watts.}$$

Similarly, on reference to the curve of eddy-current losses on p. 105, we find that, at this flux-density, the eddy-current loss for 1 cubic inch of iron at 1 cycle per second for plates of 20 mils thickness is 0·00024 watt. Now the stampings of this armature are only 18 mils thick, therefore the eddy-current loss in the teeth is :—

$$720 \times 0{\cdot}00024 \times (22{\cdot}5)^2 \times \frac{(0{\cdot}018)^2}{(0{\cdot}020)^2} = 70 \text{ watts;}$$

making a total iron-loss in the teeth of 690 watts.

The number of cubic inches of iron in the armature core-body is :—

$$\{(29{\cdot}75)^2 \times 0{\cdot}78 \times 9\} - \{(18)^2 \times 0{\cdot}78 \times 9\}$$
$$= 3905 \text{ cubic inches.}$$

At full-load the flux-density is about 69,000 lines per square inch. From the curves, taking as before the hysteretic constant as $\eta = 0{\cdot}003$, we find that 0·013 watt is lost per cubic inch of iron at 1 cycle per second. Hence, the hysteresis loss in the core-body is :—

$$3905 \times 0{\cdot}013 \times 22{\cdot}6 = 1140 \text{ watts.}$$

For the eddy-current loss, we find that at this flux-density and at 1 cycle per second, and for stampings 20 mils thick

0·00008 watt is lost, so that the eddy-current loss in the core-body will be :—

$$3905 \times 0{\cdot}00008 \times (22{\cdot}5)^2 \times \frac{(0{\cdot}018)^2}{(0{\cdot}020)^2} = 128 \text{ watts,}$$

making the total iron-loss in the core-body 1268 watts.

Adding together the losses in the teeth and core-body, we have as the total iron-loss of the machine :—

$$w_i = 1958 \text{ watts.}$$

3. *Excitation Loss.*—The total resistance of the shunt winding is 61 ohms, therefore the current through the shunt-coils at full-load is—

$$\frac{250}{61} = 4{\cdot}1 \text{ amperes,}$$

$$\begin{aligned} w_x &= 4{\cdot}1 \times 250 \\ &= 1025 \text{ watts.} \end{aligned}$$

4. *Commutator Losses.*—Upon the commutator are pressed twenty-four brushes (4 per pole), and the area of each brush is about 1·75 square inches, making a total area of brush contact of 42 square inches. The 600 amperes go in through 21 square inches and come out through the other 21 inches.

Assuming the contact resistance to be 0·03 ohm per square inch, we have for the C_2R loss at the commutator :—

$$\begin{aligned} &2 \times 600 \times 600 \times 0{\cdot}03 \div 21 \\ &= 1032 \text{ watts.} \end{aligned}$$

The peripheral speed of the commutator is 2475 feet per minute.

Assuming brush pressure to be 1·5 pounds per square inch and the friction coefficient to be 0·3, we have for the friction of the commutator

$$\frac{1{\cdot}5 \times 0{\cdot}3 \times 42 \times 2475 \times 746}{33{,}000}$$

$$= 1055 \text{ watts.}$$

Hence the full-load loss by brush resistance and friction is

$$w_b = 2090 \text{ watts.}$$

5. *Friction and Ventilation Losses.*—Owing to this being a rope-driven machine the friction losses will come out rather high, say 3 per cent. of the output, that is

$$w_f = 4500 \text{ watts.}$$

The total full-load loss is obtained by taking the sum of the separate losses, that is

$$\begin{aligned} w &= w_c + w_i + w_x + w_b + w_f; \\ &= 1738 + 1958 + 1025 + 2090 + 4500; \end{aligned}$$

or, in total, 11,310 watts; say 11·3 kilowatts.

Therefore the full-load efficiency is:—

$$\eta = \frac{150}{(150 + 11{\cdot}3)} = 93 \text{ per cent.}$$

Probable Heating.—(*a*) Armature. From the drawings the heat-radiating surface of the armature is found to be about 2500 square inches.

The peripheral speed is

$$\frac{33 \times 3{\cdot}1416 \times 450}{12} = 2835 \text{ feet per minute.}$$

The watts lost in the armature at full-load are:—

Iron loss	1958
Copper loss	1440

making the watts wasted per square inch of radiating surface

$$\frac{3398}{2500} = 1{\cdot}36 \text{ watts per square inch.}$$

A reference to the lower curve of Fig. 99 shows that the temperature-rise per watt per square inch, for a peripheral speed of 3835 feet per minute, is for large well-ventilated armatures 25 deg. C.

Hence we have

$$\theta_a = 25 \times 1{\cdot}36 = 27{\cdot}2 \text{ deg. C.}$$

(*b*) Field-magnet system. Here the radiating surface is about 342 square inches per bobbin, or a total of 2052 square inches. The watts lost in the shunt coil have been already estimated at 1025, and the watts lost in heat in the series winding are

$$(600 \times 600 \times 0{\cdot}00083) = 298 \text{ watts.}$$

Hence the probable rise of temperature of the field coil is

$$\frac{(1025 + 298) \times 75}{2052}$$

$$\theta_m = 49 \text{ deg. C.}$$

(*c*) Commutator. For the probable heating of this part of the machine we have (p. 520)

$$\theta_c = \frac{46{\cdot}5 \times 2090}{21 \times 3{\cdot}14 \times 9{\cdot}5\,(1 + 0{\cdot}0005 \times 2475)}$$

$$\theta_c = 69 \text{ deg. C.}$$

Sparking.—We have already found the value of the cross-magnetizing ampere-turns, namely,

$$X_c = 6500$$

The ampere-turns required for the gap and teeth at full-load are about 16,700, the flux-density in the former being 65,000.

Hence the flux-density under the entrant pole-horn is approximately

$$65{,}000 \times \frac{16{,}700 - 6500}{16{,}700} = 39{,}700 \text{ lines per square inch,}$$

which is amply sufficient for commutation (see p. 276).

Applying the sparking criteria described on p. 278 and taking the formulæ there given, we find the present data are

$$B_s = 65{,}000$$
$$q_1 = 570$$
$$K = 248$$
$$k_2 = 2$$
$$g = 0{\cdot}31$$
$$d = 33$$

whence $Y_1 = 65{,}000 \times 2 \div 570 = 228.$

$$Y_2 = 248 \times 0{\cdot}31 \div 33\,(1 + 2) = 0{\cdot}78$$

Thus Y_1 and Y_2 are both above the minimum values prescribed on p. 278, and we may assume that the machine will not spark.

Fig. 398 gives the test-curves of the performance of this machine running on the testing-bed of the factory.

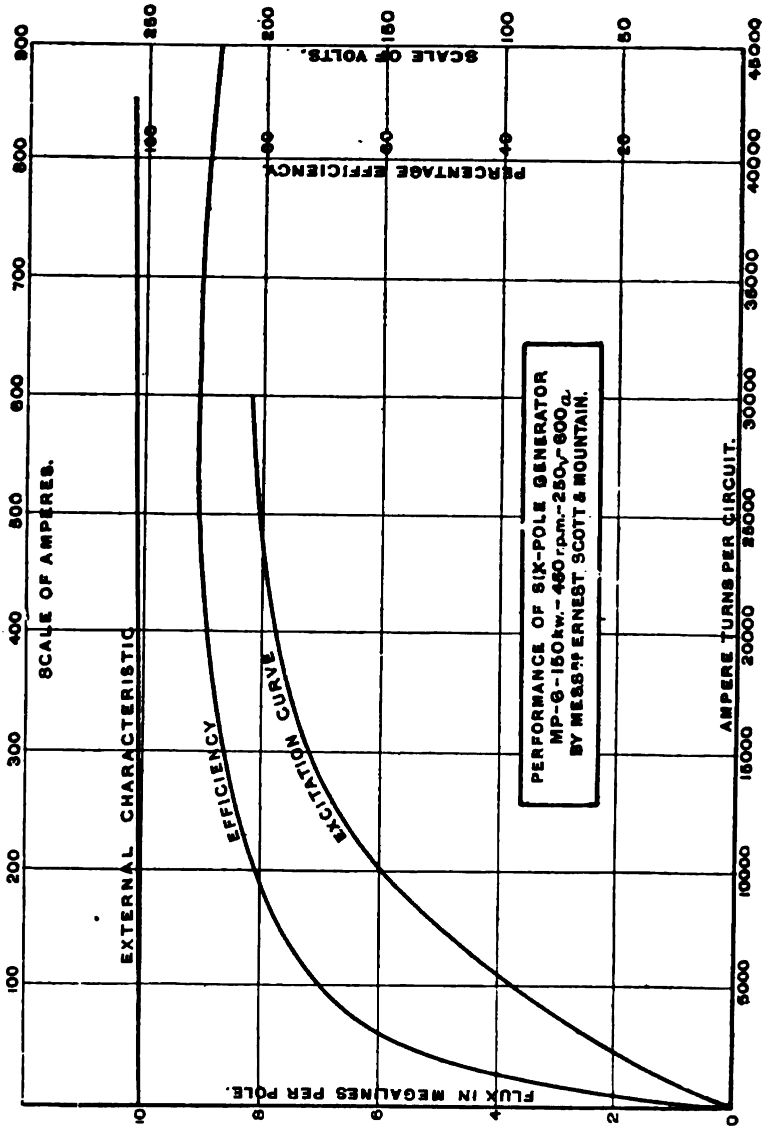


FIG. 398.—FACTORY TESTS OF SCOTT AND MOUNTAIN 6-POLE GENERATOR.

Example II.—OVER-COMPOUNDED MULTIPOLAR TRACTION GENERATOR WITH SLOTTED DRUM ARMATURE.

Built by The Walker Manufacturing Company.

M P—10—440—85—550 volts—800 amperes.

The leading dimensions and data given below and in Figs. 399, 400 and 401, were kindly placed at the disposal of the author by the late Prof. S. H. Short, formerly the company's chief engineer.

General Specification.

Full-load kilowatts	440
„ terminal volts	550
„ amperes	800
No-load terminal volts	500
Revolutions per minute	85
Peripheral speed, feet per minute	2000
Number of poles	10
Nature of load	Traction

Dimensions (in inch units).

Armature—

Core-disks, external diameter	90
„ internal „	68
Number of slots	464
Depth of slot	1·75
Width „	0·3
Pitch „ (average)	0·6
Depth of iron in core	9·25
Gross length of core	18·5
Iron „ „	13·8
Total number face conductors	1856
Conductors per slot	4
Style of winding	Parallel
Dimensions of conductor, bare	0·06 × 0·71
„ „ „ insulated	0·08 × 0·75
Section of conductor	0·0426
Mean length, one turn	103

Field-magnets.

Diameter of bore	91
Polar angle	27°
Turns per pair of poles, shunt	2200
„ „ „ series	19
Mean length, one shunt turn	79
„ „ „ series „	78
Diameter shunt conductor, bare	0·162
„ „ „ insulated	0·185
Section (square inches)	0·0206
Dimensions series conductor, bare	5 of 0·75 × 0·28
Dimensions series conductor, insulated	5 of 0·79 × 0·32
Section of series conductor	5 × 0·21
Shunt current at no-load	10·7
„ „ full-load	11·8

Commutator.

Diameter	70
Useful length	8·5
Number of segments	928
Bars per brush	3·3
Brushes per pole	3
Size of brushes	¾ × 2½ × 2½
Area at commutator face	1·95

In this machine, which is a representative type of tramway generator, the wrought-iron magnet-cores are cast in with the magnet-yoke, and are of square section. The pole-horns are secured to the poles after the field bobbins have been slipped on. The series winding is not wound over the shunt winding, but in a separate compartment of the bobbin, as may be seen from the section of the latter given in Fig. 400. The armature slots are quite straight with slightly rounded corners, and of width equal to the average width of tooth.

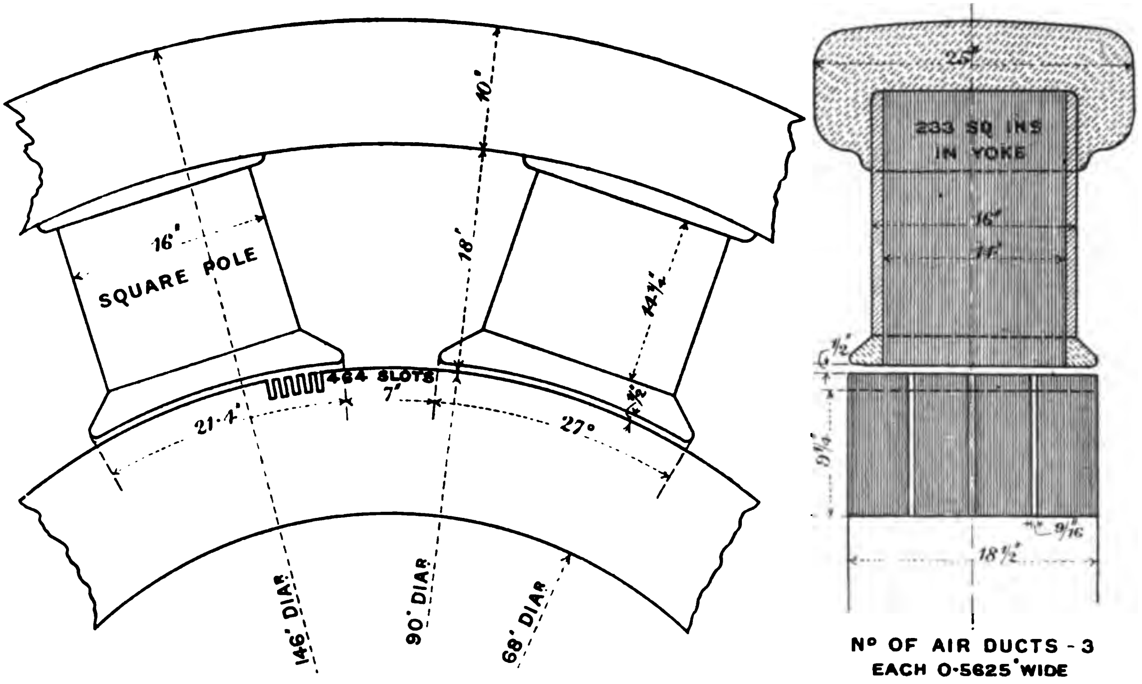


FIG. 399.—WALKER COMPANY'S TRACTION GENERATOR M P—10—440—85: SKETCH OF PRINCIPAL DIMENSIONS.

There are four ventilating ducts in the armature, each 0·5625 inch wide, while the paper insulation between the core-disks deducts 15 per cent. from the gross section of the core. The ratio of nett length to gross length of armature iron is thus 0·745. There are ten parallel circuits in the armature, and ten sets of carbon brushes at 36 degrees apart around the commutator.

The design of this machine may now be analysed in precisely the same manner as in the last case. The first thing to do is to construct the saturation curve and no-load characteristic. We have

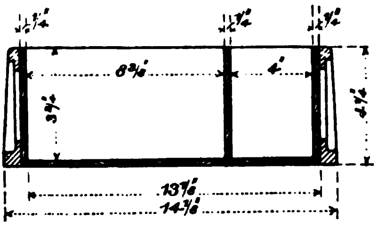


FIG. 400.—DIMENSIONS OF BOBBIN.

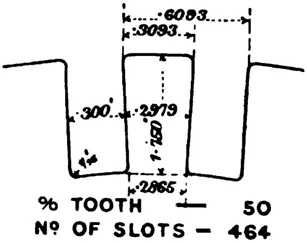


FIG. 401.—DIMENSIONS OF SLOTS.

$$E = \frac{85}{60} \times 1856 \times N_a \times 10^{-8};$$

$$E = 0·0000263 \times N_a.$$

The dispersion coefficient of this machine has been determined experimentally by the makers, and found to be 1·13 and nearly independent of the load. Hence

E	N_a	N_m
460	17,500,000	19,750,000
500	19,000,000	21,500,000
520	19,750,000	22,300,000
560	21,300,000	24,900,000
580	22,000,000	24,900,000
600	22,800,000	25,800,000

From Fig. 399 and the data already given above, we obtain

Length of mean magnetic path in—

Magnet yoke (inches)	50
Two magnet cores	35
Armature core	33
Two teeth	3·5
Two air-gaps	1

And for the magnetic areas—

for the yoke	25 × 9·32 = 233	sq. in.
„ magnet cores	16 × 16 = 256	„
„ armature core	9·25 × 13·8 = 128	„

The actual number of teeth under one pole is

$$464 \times \frac{27}{360} = 34 \cdot 8.$$

As the air-gap is on the whole large compared with the diameter of the armature, and as the teeth are worked at high flux-densities, the flux will spread considerably, and for this reason we will take the number of teeth transmitting the flux as being 37. The average pitch of the slots is 0·6, and their width 0·3 inch. Hence the area of the teeth is

$$37 \times (0 \cdot 6 - 0 \cdot 3) \times 13 \cdot 8 = 154 \text{ square inches.}$$

Also, owing to the high densities in the teeth, and the rounded corners of the latter, the area of the air-gap will be very nearly the same as that of the pole-face. This latter is

$$\frac{91 \times 3 \cdot 1416 \times 27 \times 18 \cdot 5}{360} = 397 \text{ square inches.}$$

This figure would adequately represent the air-gap area if there were no ventilating ducts in the armature core. Reducing the polar area obtained above in the proportion of the length without ducts to the length of pole-face, we obtain

$$\text{Area of air-gap} = \frac{397 \times 16 \cdot 25}{18 \cdot 5} = 348 \text{ square inches.}$$

The two tabulations below give the working out for two points of the saturation curve, namely, when E = 520 and E = 560. The tooth flux-densities given are the true values, obtained from the apparent values by means of curve A A of Fig. 79. The values of ampere-turns per inch (δ) have been obtained from the magnetization curves of Plate I.

E = 520; N_a = 19,750,000; N_m = 22,300,000.

Part of Machine.	Material.	Magnetic Length.	Magnetic Area.	Flux-density.	Values of δ (from Curve).	Ampere-turns.
Yoke . .	Cast iron	50	233	47,600	92	4600
Two magnet cores .	Wrought iron	35	256	87,000	28·5	1000
Two air-gaps	Air	1	348	56,700	[0·3133]	18,100
Two teeth .	Iron stampings	3·5	154	123,000	700	2450
Armature core	,,	33	128	77,000	8	264
		Total ampere-turns per pair of poles				26,414

E = 560; N_a = 21,300,000; N_m = 24,000,000.

Part of Machine.	Material.	Magnetic Length.	Magnetic Area.	Flux-density.	Values of δ (from Curve).	Ampere-turns.
Yoke . .	Cast iron	50	233	51,400	115	5750
Two magnet cores .	Wrought iron	35	256	93,600	45	1575
Two air-gaps	Air	1	348	61,100	[0·3133]	19,200
Two teeth .	Iron stampings	3·5	154	131,000	1400	4900
Armature core	,,	33	128	83,000	11	365
		Total ampere-turns per pair of poles				31,790

In the same way we calculate other points of the curve, obtaining

When E = 460, necessary ampere-turns = 20,710
,, = 500 ,, ,, = 24,040
,, = 580 ,, ,, = 34,960
,, = 600 ,, ,, = 39,100

By plotting the curve connecting these six points we obtain the working part of the no-load characteristic, as shown in Fig. 402. We have then

Necessary ampere-turns at no-load = X_1 = 24,250.

We will now proceed to find the necessary ampere-turns at full-load. These will be greater than those required at no-load by an amount depending upon—

(1) Amount of over-compounding asked for.
(2) The value of the full-load lost volts.
(3) Amount of armature demagnetization.
(4) „ „ distortion.

Now, there are 1856 conductors in series round the whole armature, that is, 928 turns. From the data already given (p. 515), we thus have for 40° C.

$$r = \frac{9{\cdot}2 \times 928 \times 103}{12 \times 0{\cdot}0426 \times 10^6} = 1{\cdot}72 \text{ ohms}$$

and the resistance of the armature at this temperature is thus

$$r_a = \frac{1{\cdot}72}{4 \times (5)^2} = 0{\cdot}0172 \text{ ohms.}$$

There are 19 turns of series conductors per pair of poles, the mean length of one turn being (78 ÷ 12) = 6·5 feet. Hence the total resistance of the series winding at 40° C. is

$$r_m = \frac{9{\cdot}2 \times 6{\cdot}5 \times 19 \times 5}{1\ 05 \times 1{,}000{,}000}$$
$$= 0{\cdot}00542 \text{ ohm.}$$

Hence the total resistance of the main current circuit in the machine is (0·0172 + 0·0054) = 0·0226 ohm. The full-load drop is therefore

$$e = 800 \times 0{\cdot}0226 = 18{\cdot}1 \text{ volts.}$$

Now, the terminal pressure of the machine at full-load is to be 550, corresponding to an over-compounding of 10 per cent. Hence the armature must generate at full-load (550 + 18·1) = 568 volts. Finding this point on the scale of ordinates of the curve, and projecting it across, we find the point

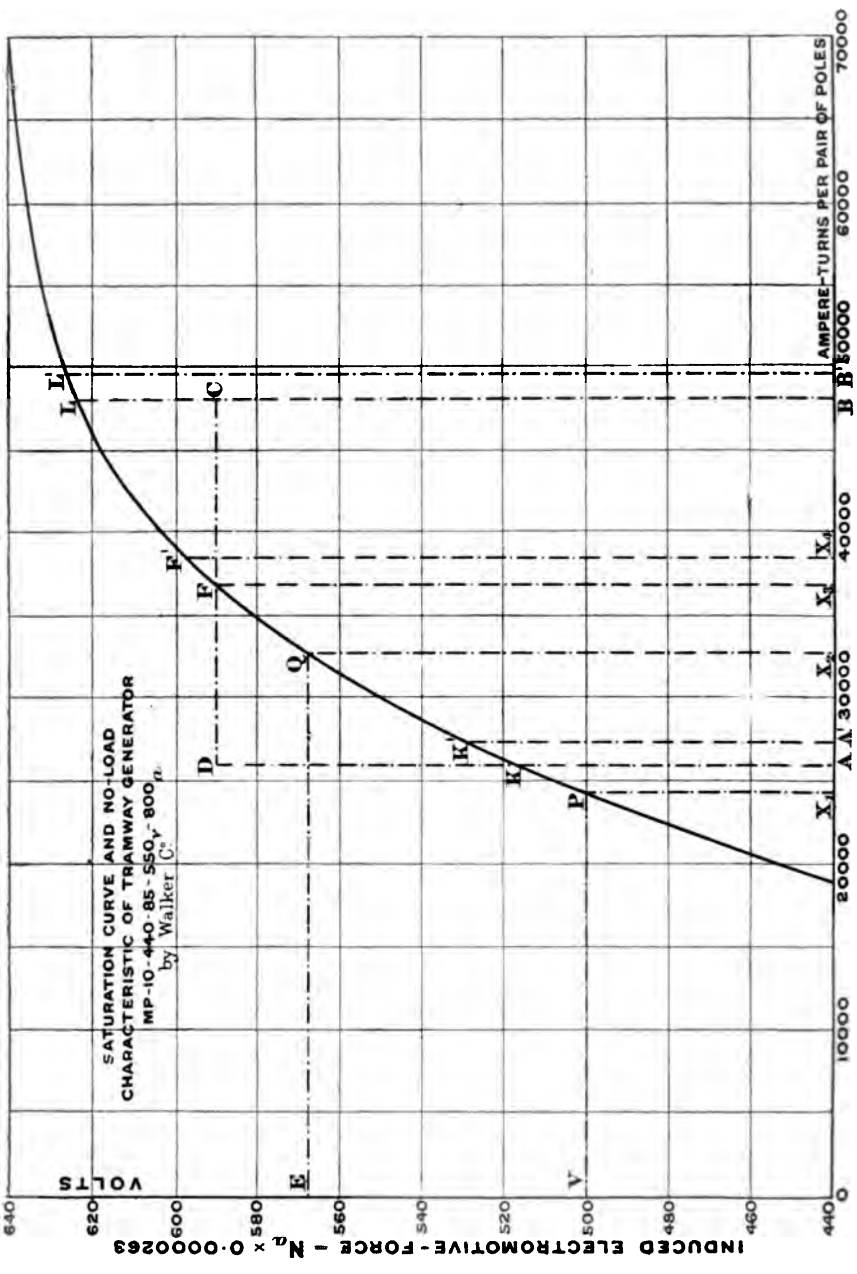


FIG. 402.—SATURATION CURVE OF WALKER 10-POLE GENERATOR.

X_2 on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at full-load if armature reaction were entirely absent.

Now, the number of slots lying between the pole-tips is

$$\frac{(36 - 27)}{360} \times 464 = 11 \cdot 5$$

and in each slot there are four conductors carrying a little over 80 amperes at full-load. Hence the demagnetizing turns of the armature at full-load, and upon the assumption that the brushes are moved right under the pole-horns, are

$$11 \cdot 5 \times 4 \times 80 = 3680.$$

The compensating ampere-turns per pair of poles are therefore

$$3680 \times 1 \cdot 13 = 4160.$$

Adding then these ampere-turns to X_2 we find X_3 as the ampere-turns necessary at full-load, assuming that there is no drop of pressure due to the diminished permeability of the teeth at the forward pole-horn, due to distortion of the flux. But this will not be the case, owing to the high flux-densities in the armature teeth. We must therefore allow for this as explained on p. 527. For this we have :—

$$\left.\begin{array}{c}\text{Ampere-turns under}\\ \text{one pair poles}\end{array}\right\} = \frac{27}{360} \times 464 \times 4 \times 80$$

$$= 11{,}100.$$

We set off, therefore 11,100 ampere-turns from each side of the point X_3 upon the scale of abscissæ, and obtain thus the points A and B, which represent the backward and forward pole-horns respectively. If distortion of the main flux were absent, the latter would be proportional to the area A B C D. But as this is not the case, it is proportional to the smaller area A B L K. In order to make this area equal to that of the rectangle, we must shift the point F higher up the curve to the position F′, so that

$$\text{area } A' B' L' K' = \text{area } A B C D.$$

In this manner we obtain the point X_4 as the necessary ampere-turns at full-load. Their value is

$$X_4 = 38{,}500.$$

Comparing our results with the actual values of the running machine we have—

Output.	Calculated Values.	Actual Values.
At no-load .	24,250	23,600
At full-load .	38,500	41,200

Showing that the calculated value is about 2½ per cent. too high at no load, and 6½ per cent. too low at full-load, which is good enough. Had the magnetic properties of the iron used for this machine been definitely known, a somewhat better result might have been obtained.

Calculation of Full-Load Efficiency.—

(1) *Copper-loss.* This is

$$w'_c = 800 \times 800 \times 0{\cdot}0226$$

$$w'_c = 14{,}500.$$

(2) *Iron-loss.* The weight of iron in the teeth is

$$1{\cdot}75 \times 0{\cdot}3 \times 13{\cdot}8 \times 464 \times 0{\cdot}28$$
$$= 944 \text{ pounds.}$$

The frequency of reversal is

$$\frac{85}{60} \times 5 = 7{\cdot}1 \text{ periods per second.}$$

They are worked at a flux-density of about 132,000 lines per square inch at full-load. From the curves of Fig. 54, p. 101, we see that at a flux-density of 80,000 lines per square inch and a frequency of 30 ∿ the hysteresis watts per pound are about 2·1, and the eddy loss 0·8 watt per pound. Therefore the hysteresis loss in the teeth is

$$\frac{944 \times 2{\cdot}1 \times 7{\cdot}1 \times (132000)^{1{\cdot}6}}{30 \times (80000)^{1{\cdot}6}}$$
$$= 1040 \text{ watts.}$$

And the eddy-current loss in the teeth is

$$\frac{944 \times 0{\cdot}8 \times (7{\cdot}1)^2 \times (132{,}000)^2}{(30)^2 \times (80000)^2}$$
$$= 115 \text{ watts,}$$

making a total iron-loss in the teeth at full-load of 1155 watts.

The weight of the armature core is

$$\left(\frac{86{\cdot}5 + 68}{2} \times 3{\cdot}1416 \times 128\right) \times 0{\cdot}28$$
$$= 8750 \text{ pounds.}$$

At full-load it is worked at a flux-density of about 85,000 lines per square inch. From the curves of iron-loss we see that at 30 periods per second and at this flux-density the hysteresis loss is about 2·3 watts per pound, and the eddy-current loss 0·9 watt per pound. Hence the hysteresis loss in the core is

$$8750 \times 2{\cdot}3 \times \frac{7{\cdot}1}{30} = 4760 \text{ watts.}$$

And the eddy-loss is

$$8570 \times 0{\cdot}9 \times \frac{(7{\cdot}1)^2}{(30)^2} = 440 \text{ watts.}$$

So that the total iron-loss in the core is 5200 watts. Adding this to the loss in the teeth we have as the total iron-loss of the generator at full-load

$$w_i = 6355, \text{ say } 6360 \text{ watts.}$$

(3) *Excitation loss.* There are 2200 shunt-turns per pair of poles. Taking the previously calculated value of full-load ampere-turns, we have as the shunt current at full-load

$$\frac{38{,}500 - (19 \times 800)}{2200} = 10{\cdot}6 \text{ amperes.}$$

Hence

$$w_x = 10{\cdot}6 \times 550 = 5840 \text{ watts.}$$

(4) *Commutator loss.* There are altogether 30 carbon brushes upon the commutator, the section of each at the commutator face being 1·95 square inches. The total area of contact is thus 58·5 square inches. Assuming the contact

resistance to be 0·03 ohms per square inch of contact area (p. 241) we have as the $C^2 R$ loss at the commutator

$$2 \times 800 \times 800 \times \frac{0·03}{29·75} = 1320 \text{ watts.}$$

The peripheral speed of the commutator is

$$\frac{70 \times 3·1416 \times 85}{12} = 1560 \text{ feet per minute.}$$

Assuming the brush pressure to be 1·5 pounds per square inch, and that the friction coefficient is 0·3, we have as the friction loss of the commutator

$$\frac{1·5 \times 58·5 \times 1560 \times 0·3 \times 746}{33{,}000}$$
$$= 930 \text{ watts.}$$

Hence the total loss by brush resistance and by friction is

$$w_b = 2250 \text{ watts.}$$

(5) *Friction and ventilation losses.*—Taking these as 1 per cent. of the full-load output—an ample estimate—we have

$$w = 4400 \text{ watts.}$$

The total full-load loss is the sum of the five losses above, or

$$w = w_c + w_i + w_x + w_b + w_f$$
$$w = 33{,}390 \text{ watts.}$$

Therefore the full-load efficiency is

$$\frac{440}{(440 + 33·9)} = 0·928$$
$$\eta = 92·8 \text{ per cent.}$$

Probable Heating.—

(*a*) Armature. From the drawings the heat-radiating surface of the armature is found to be about 11,000 square inches. The peripheral speed is

$$\frac{90 \times 3·1416 \times 85}{12} = 2000 \text{ feet per minute.}$$

The watts lost in the armature at full-load are

Iron-loss . . 6380
Copper-loss . . $800 \times 800 \times 0{\cdot}0172 = 11{,}000$

making the watts wasted per square inch of radiating surface

$$\frac{17{,}380}{11{,}000} = 1{\cdot}58 \text{ watts per square inch.}$$

A reference to the lower curve of Fig. 99, p. 187, shows that the temperature-rise per watt per square inch for a peripheral speed of 2000 feet per minute is 30° C. Hence we have

$$\theta_a = 30 \times 1{\cdot}58 = 47{\cdot}5 \text{ deg. Centig.}$$

(*b*) Field-magnet System. Here the radiating surface is about 2000 square inches per bobbin, or a total of 20,000 square inches. The watts lost in the shunt coils have been already estimated at 5840, and the watts lost in heating the series winding are

$$(800 \times 800 \times 0{\cdot}0054) = 3460 \text{ watts.}$$

Hence the probable rise of temperature of the field-coils is

$$\frac{(5840 + 3460) \times 75}{20{,}000}.$$

$$\theta_m = 35 \text{ deg. Centig.}$$

(*c*) Commutator. For the probable heating of this part of the machine we have (p. 520)

$$\theta_c = \frac{46{\cdot}5 \times 2250}{70 \times 3{\cdot}14 \times 8{\cdot}5\,(1 + 0{\cdot}0005 \times 1560)}$$

$$\theta_c = 28 \text{ deg. Centig.}$$

Sparking.—We have already found the value of the cross-magnetizing ampere-turns, namely,

$$X_c = 11{,}100.$$

The ampere-turns required for the gap and teeth at full-load are about 25,000, the flux-density in the former being about 61,000. Hence the flux-density under the entrant pole-horn is approximately

$$61{,}000 \times \frac{25{,}000 - 11{,}000}{25{,}000}$$

$$= 34{,}000 \text{ lines per square inch,}$$

which is a sufficient value for sparkless reversal.

Applying the two *criteria* of sparking (p. 278), we have the following data:—

$B_3 = 19{,}000$ lines per square inch;
$d = 90$ inches diameter of core;
$K = 928$ total segments of commutator;
$k_2 = 3{\cdot}3$ number of segments of commutator short-circuited at once;
$g = 0{\cdot}5$ inches across gap;
$q_1 = 1856 \times 80 \div 90\pi = 525$ ampere-conductors per inch at full-load;

whence we get:

$$Y_1 = 19{,}000 \times 3{\cdot}3 \div 525 = 119;$$
$$Y_2 = 928 \times 0{\cdot}5 \div 90\,(1 + 3{\cdot}3) = 1{\cdot}2.$$

Now for a sparkless result (see p. 278) in this class of machine the conditions are that Y_1 should not be *less* than 38, nor Y_2 less than 1·2. From both points of view, therefore, the criterion is satisfied by the design. As a matter of fact, the machine runs quite sparklessly with adjusted brushes; and even with *fixed* brushes runs nearly sparklessly at all loads up to 25 per cent. overload.

The flux-density in the gap being 60,000, and the specific load 525 ampere-conductors per inch, the *stiffness-ratio* (p. 277) is no less than 112; and as the volts per segment are 5·9, the *commutation ratio* is 19.

Arrangement	Two in parallel per slot
Style of winding	Parallel
Dimensions of each conductor, bare	(0·118 × 0·785)

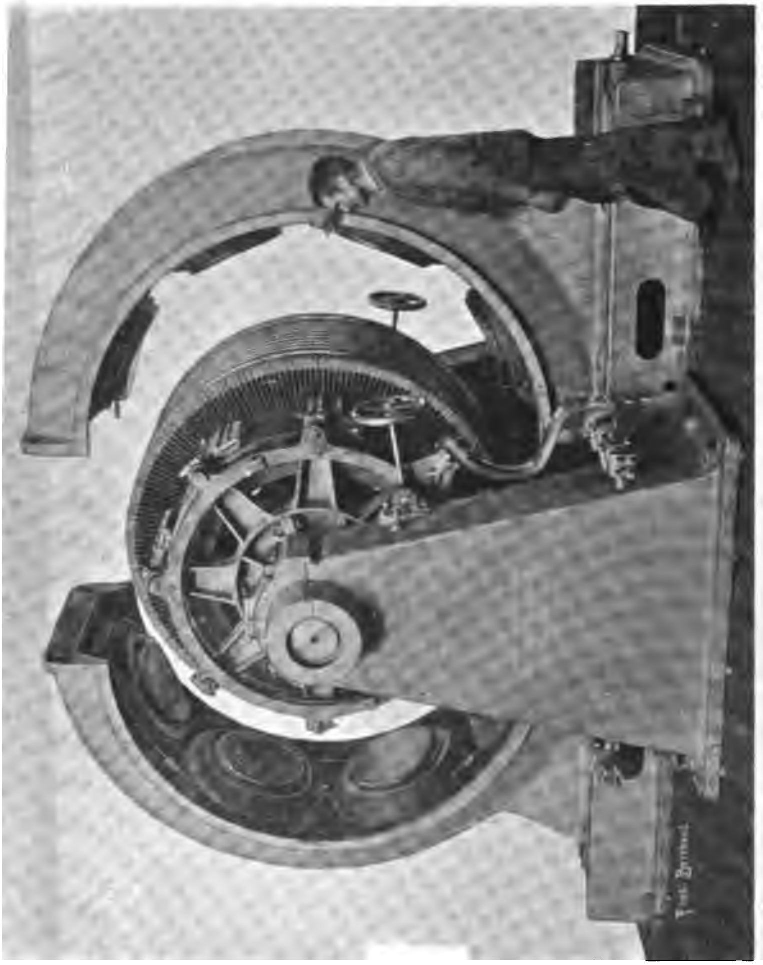


FIG. 403.—BROWN'S ELECTRO-METALLURGICAL GENERATOR. M P C 8 – 480 – 250 – 120 volts – 4000 amperes.

Dimensions of each conductor, insulated	(0·158 × 0·825)
Section of each conductor	0·093
Mean length, one armature turn	9·5 feet

Field-magnets.

Diameter of bore	70
Polar angle	30°
Turns per pair of poles	612
Mean length of one turn	6 feet

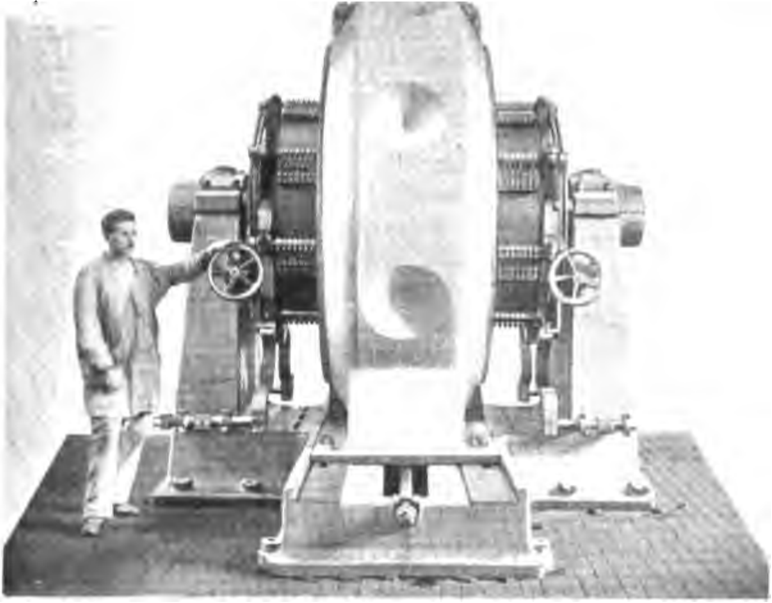


FIG. 404.—BROWN'S ELECTRO-METALLURGICAL GENERATOR.

Diameter of wire, bare	0·303
„ „ insulated	0·326
Section of wire	0·072
Shunt current, no-load (observed)	37
„ „ full-load (observed)	48

Commutators (two).

Diameter of each	51
Number of segments	196
Active length	10·5

An inspection of the drawings shows that the magnet cores are of circular section, cast in one piece with the yokes, and without polar extensions. The field frame is cast in two pieces and bolted together at top and bottom. All the field-bobbins are connected in series. The armature-slots are straight, and of the dimensions given above. It has two ventilating apertures, each 0·59 inch wide, and the core-disks are insulated with paper, deducting 15 per cent. from the gross section. The armature has two distinct windings, each having its own commutator. There are eight parallel circuits in each, and eight sets of brushes at 45° apart for each commutator.

We will first construct the saturation-curve of the machine. We have

$$E = n \times Z \times N_a \div 10^8$$

$$\text{or } E = \frac{250}{60} \times 196 \times N_a \div 10^8$$

$$E = 0{\cdot}00000815\ N_a$$

A reference to the table of leakage coefficients given on p. 137 gives $\nu = 1{\cdot}18$ for machines of this type and output. Hence we have

E	N_a	N_m
180	22,050,000	26,000,000
160	19,600,000	23,200,000
140	17,200,000	20,250,000
120	14,700,000	17,400,000
100	12,250,000	14,500,000
80	9,800,000	11,600,000

From the drawings we obtain :—

Length of mean magnetic path in magnet yoke .	40
" " " two magnet cores .	27
" " " armature core . .	30
" " " two teeth . .	3·4
" " " two air-gaps . .	1·0

And for the magnetic areas :—

For the yoke . $5\cdot5 \times 23\cdot6 = 130$ square inches.
„ magnet cores $(18\cdot5)^2 \times 0\cdot785 = 269$ „ „
„ armature core $6\cdot3 \times 15\cdot7 = 99$ „ „

As will be noticed, the sides of the teeth are nearly parallel. The polar angle being 30°, we have for the number of teeth under one pole

$$\frac{392 \times 30}{360} = 32\cdot6.$$

The average pitch of the slots is 0·54 inch, and hence the width of tooth = $(0\cdot54 - 0\cdot216) = 0\cdot324$ inch.

Consequently the area of the teeth under each pole may be taken as

$$32\cdot6 \times 0\cdot324 \times 15\cdot7 = 166 \text{ square inches.}$$

The air-gap area will be the mean of the tooth-area and pole-face area, or

$$\frac{270 + 166}{2} = 218 \text{ square inches.}$$

We have now all the data for constructing the saturation curve and the no-load characteristic. It will be sufficient here to work out two points of the curve, as the method is the same for them all. Taking the points $E = 130$ and $E = 100$ as examples, we obtain the two tabulations given below. The values of ampere-turns per inch, δ, have been taken from the magnetization curves given in Plate I.

$E = 100$; $N_a = 12{,}250{,}000$; $N_m = 14{,}500{,}000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-density.	Value of δ (from Curve).	Ampere-turns.
Yoke . .	Cast steel	40	2 × 130	55,700	10·6	424
Two magnet cores .	„	27	269	54,000	10	270
Two air-gaps	Air	1	218	56,200	[0·3133]	17,620
Two teeth .	Iron stampings	3·4	166	74,000	7	24
Armature core	„	30	2 × 99	62,000	4	120
		Total ampere-turns per pair of poles.				18,458

$E = 130$; $N_a = 15{,}900{,}000$; $N_m = 18{,}800{,}000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-density.	Value of δ (from Curve).	Ampere-turns.
Yoke . .	Cast steel	40	2 × 130	72,300	16·8	670
Two magnet cores .	,,	27	269	70,000	15·5	420
Two air-gaps	Air	1	218	73,000	[0·3133]	22,900
Two teeth .	Iron stampings	3·4	166	95,700	22·6	77
Armature core	,,	30	2 × 99	80,300	9	270
		Total ampere-turns per pair of poles.				24,337

In the same way we find other points on the curve, obtaining thus

E = 180 ; Ampere-turns = 41,500
,, 160 ; ,, = 32,750
,, 140 ; ,, = 27,000
,, 120 ; ,, = 22,200

By plotting the curve with these various values, we obtain the saturation curve of the machine as shown in Fig. 405, in which the no-load ampere-turns required are given by the abscissa X_1.

We next proceed to estimate the excitation required at full-load. As the teeth are worked at quite normal flux-densities in this machine, it will not be necessary to compensate for diminished permeability due to the distortion of the main flux. In other words, we have only to allow for the lost volts and for the demagnetizing effect of the armature current in our calculations.

In each armature there are 196 slots, containing the equivalent of one bar per slot. That is to say, 98 turns, and the copper section per slot is $(2 \times 0{\cdot}093) = 0{\cdot}186$ square inches. Hence we have for the resistance of the whole of the winding in each armature at 40° C.

$$r = \frac{9{\cdot}2 \times 98 \times 9{\cdot}5}{0{\cdot}186 \times 10^6}$$
$$= 0{\cdot}046 \text{ ohms.}$$

Therefore the resistance of each armature is

$$\frac{r}{4 \times p^2} = \frac{0 \cdot 046}{64} = 0 \cdot 00072.$$

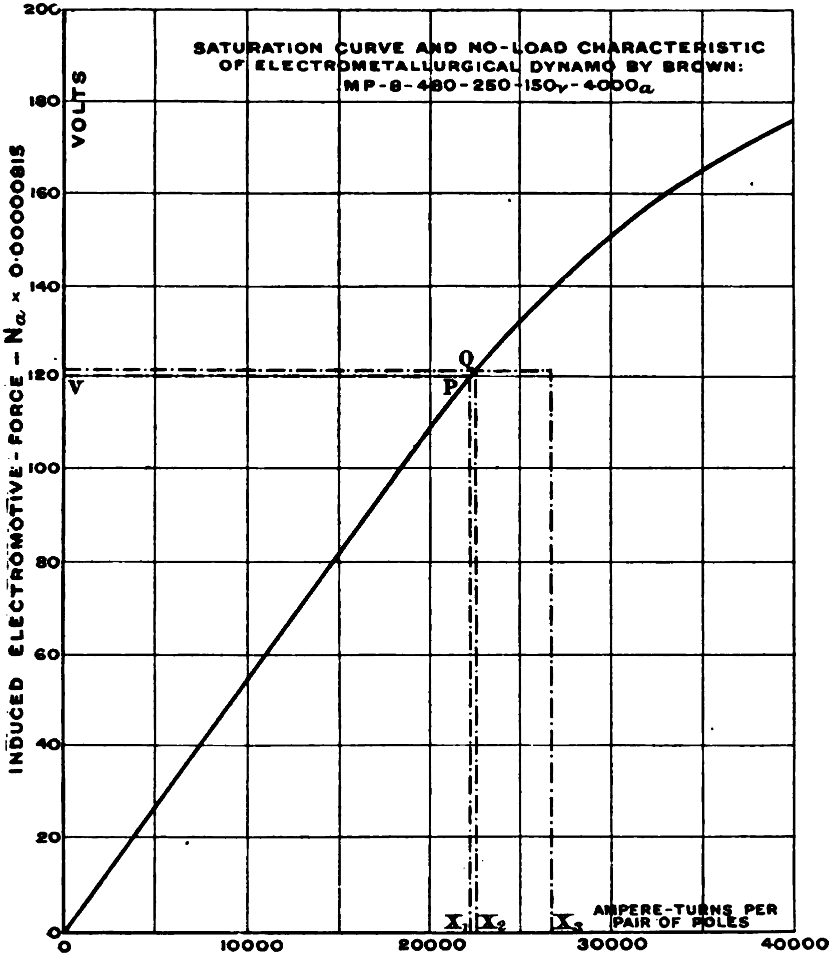


FIG. 405.—SATURATION CURVE OF BROWN'S ELECTRO-METALLURGICAL DYNAMO.

And as the two armatures are in parallel with one another,

$$r_a = \frac{0 \cdot 00072}{2} = 0 \cdot 00036 \text{ ohm.}$$

The lost volts at full-load are therefore

$$e = 4000 \times 0{\cdot}00036 = 1{\cdot}44.$$

So that at full-load the total induced electromotive-force must be, say, 121·5 volts. Projecting this value on the scale of ordinates across to the curve, we obtain the abscissa X_2 as the necessary ampere-turns.

Now the slots lying between the pole-tips are

$$\frac{15}{360} \times 392 = 16{\cdot}3$$

and the volume of current in each at full-load is 250 amperes. The demagnetizing ampere-turns of the armature are therefore

$$16{\cdot}3 \times 250 = 4080,$$

assuming that the brushes are just under the pole-tips at this load. Adding then this number, multiplied by the leakage-coefficient, 1·18, to X_2 we obtain the point X_3 as giving the necessary ampere-turns at full-load. Their value is

$$X_3 = 26700.$$

The tabulation below gives a comparison of our calculated values with the actual values observed on the running machine.

Output.	Calculated Values.	Observed Values.
At no-load .	22,200	22,700
At full ,, .	26,700	29,400

It will be noticed that the full-load calculation comes out somewhat too low. The reason for this is not far to seek. We assumed throughout that the leakage coefficient at full-load is no higher than that at no-load, which is probably not the case. Also, owing to the collection by the carbon brushes, the contact resistance of which is comparable to that of the armature winding, there will be a further drop across them which has not been allowed for in the full-load calculation.

Calculation of full-load efficiency—

(1) *Copper-loss.* For this we have

$$w = 4000 \times 4000 \times 0{\cdot}00036$$

$$w_c = 4160 \text{ watts.}$$

(2) *Iron-loss.* The weight of iron in the teeth is

$$1{\cdot}7 \times 0{\cdot}324 \times 15{\cdot}7 \times 392 \times 0{\cdot}28$$
$$= 950 \text{ lbs.}$$

The frequency of reversal is

$$\frac{250}{60} \times 4 = 16{\cdot}6 \sim.$$

At full-load they are worked at a flux-density of about 90,000 lines per square inch. Reference to the iron-loss curves of Fig. 54 tells us that at 30 ~ and this flux-density the hysteresis-loss is 2·5 watts per pound of iron, and the eddy-current loss about 1·0 watt per pound. Therefore the hysteresis-loss in the teeth is

$$950 \times 2{\cdot}5 \times \frac{16{\cdot}6}{30} = 1315 \text{ watts}$$

and the eddy current loss is

$$950 \times 1{\cdot}0 \times \frac{(16{\cdot}6)^2}{(30)^2} = 291 \text{ watts,}$$

making a total iron-loss in the teeth of 1606 watts.

The weight of the armature-core is

$$\left(\frac{65{\cdot}6 \times 53}{2} \times 3{\cdot}1416 \times 99\right) \times 0{\cdot}28$$
$$= 5190 \text{ lbs.}$$

At full-load the flux-density is about 76,000 lines per square inch. From the curves of iron-loss, p. 101, we see that at 30 ~ and at this flux-density the hysteresis-loss is about 1·9 watts per pound, and the eddy-current loss 0·7 watt. Hence the hysteresis-loss in the armature-core is

$$5190 \times 1 \cdot 9 \times \frac{16 \cdot 6}{30} = 5450 \text{ watts,}$$

and the eddy-current loss is

$$5190 \times 0 \cdot 7 \times \frac{(16 \cdot 6)^2}{(30)^2} = 1110 \text{ watts.}$$

So that the total iron-loss in the core is 6560 watts. Adding this to the loss in the teeth we have as the total iron-loss of the machine

$$w_i = 8170 \text{ watts.}$$

(3) *Excitation-loss.* There are 612 turns per pair of poles. Taking our calculated value of full-load excitation, we have

$$C_m = \frac{26700}{612} = 43 \cdot 5 \text{ amperes.}$$

Hence

$$w_x = 43 \cdot 5 \times 120 = 5210 \text{ watts.}$$

(4) *Commutator-losses.* On account of the large current being collected by carbon brushes, and also on account of the two commutators and their high peripheral speed, the commutator-losses become of very great importance in this machine. Upon each commutator are pressed 64 brushes (8 per pole), and the area of each brush is about 1·25 square inches, making a total area of brush contact of 80 square inches, the current going in through 40 sq. inches, and coming out through the other 40. Assuming the contact resistance to be 0·02 ohms per square inch (see p. 241) we have for the $C^2 R$ loss of each commutator

$$2 \times 2000 \times 2000 \times 0 \cdot 02 \div 40$$
$$= 4000 \text{ watts.}$$

Therefore of the two commutators together = 8000 watts.

The peripheral speed of the commutators is

$$\frac{51 \times 3 \cdot 1416 \times 250}{12} = 3350 \text{ feet per minute.}$$

Assuming the brush pressure to be 1·55 lbs. per square inch and that the friction coefficient is 0·3, we have for the friction loss of the two commutators

$$\frac{2 \times 1{\cdot}55 \times 80 \times 3350 \times 0{\cdot}3 \times 746}{33{\cdot}000}$$
$$= 5650 \text{ watts.}$$

Hence the total loss by brush resistance and friction is

$$w_b = 13{,}650.$$

(5) *Friction and ventilation losses.* These would be below 1 per cent. of the full-load output, that is

$$w_f = 4800 \text{ watts.}$$

The total full-load loss is obtained by taking the sum of the separate losses, that is,

$$w = w_c + w + w_x + w_b + w_f$$
$$\text{or } w = 35{,}990.$$

The output being 480 kilowatts, the full-load efficiency is

$$\frac{480}{480 + 36} = 0{\cdot}93,$$
$$\eta = 93 \text{ per cent.}$$

Probable Heating.—(*a*) Armature. From the drawings the heat-radiating surface of the armature is estimated as being about 5000 square inches. The total loss in the armature at full-load is

$$w_a = w_c + w$$
$$= 12330 \text{ watts.}$$

Hence the watts wasted per square inch of heat-radiating surface are

$$\frac{12330}{5000} = 2{\cdot}46.$$

A reference to the lower curve of Fig. 99 tells us that at the peripheral speed of this armature, namely 4500 feet per minute, there will be a final temperature-rise of 19° C. for each watt per square inch. Hence the temperature-rise of this armature will be approximately

$$\theta_a = 2\cdot46 \times 19 = 47^\circ \text{ C.}$$

(*b*) Field System. Here the heat-radiating surface is approximately 1200 square inches per bobbin. From the formula (9) given on p. 183 we can approximate to the final temperature-rise as

$$\theta_m = \frac{5210 \times 75}{1200 \times 8} = 41^\circ \text{ C.}$$

(*c*) Commutator. Using the formula given on p. 520, we have

$$\theta_c = \frac{46\cdot5 \times w_b}{S_3\,(1 + 0\cdot0005\,v)};$$

$$\theta_c = \frac{46\cdot5 \times 6825}{1690\,(1 + 0\cdot0005 \times 4000)};$$

$$\theta_c = 60^\circ \text{ C.}$$

Sparking.—The full-load cross-magnetizing ampere-turns per pair of poles in this machine are

$$\frac{30}{360} \times 392 \times 250 = 8150 = X_c.$$

At full-load the ampere-turns for the gap and teeth are about 22,000, the flux-density in the former being about 68,000. Hence the flux-density at the hindward pole-horn is approximately

$$68{,}000 \times \frac{22{,}000 - 8150}{22{,}000} = 42{,}800\,;$$

which is a reversing field of ample strength (see p. 276).

Let us now apply the two *criteria* relative to sparking described on p. 278. Taking the formulæ there given we find the present data are

$$B_3 = 68{,}000$$
$$k_2 = 2$$
$$q_1 = 392 \times 250 \div 19\pi = 452$$
$$K = 392$$
$$g = 0{\cdot}5$$
$$d = 69$$

whence we get

$$Y_1 = 68{,}000 \times 2 \div 452 = 300$$
$$Y_2 = 392 \times 0{\cdot}5 \div 69\,(1 + 2) = 0{\cdot}9.$$

Now the conditions for a good sparkless result were (see p. 278), that in a machine of this class, Y_1 should not be *less* than 38, and Y_2 not *less* than 1·2. The second condition is not indeed fulfilled; but the first is so abundantly fulfilled that we may on the whole conclude that this machine will give no trouble with its normal full-load of 4000 amperes.

Example IV.

COMPOUND-WOUND OVERTYPE DYNAMO WITH SMOOTH-CORE DRUM ARMATURE.

Designed by Mr. G. Kapp.

(Shown in Plates II., III. and IV.)

From the drawings and data furnished by the constructors of this machine we can fill in the following schedule:—

General Specification.

Full-load kilowatts	21
„ terminal volts . . .	105
„ amperes	200
Revolutions per minute . . .	780
Peripheral speed, feet per minute . .	2380
Nature of load	Lighting

Dimensions.

Armature—

Core-disks, external diameter	11·0625
„ internal diameter	6·312
Radial depth of iron	2·375
Gross length of core	16·0
Nett „ „	13·125
Diameter of finished armature	11·625
No. of face conductors	120
Dimensions of each, bare	2 × (0·11 × 0·208)
Dimensions of each, insulated	(0·25 × 0·238)
Section of conductor	0·046
Dimensions of connector, bare	(1·625 × 0·05)
Section of connector	0·08
Mean length one armature turn = two connectors plus two conductors	68·32

Field-magnets.

Material	Wrought-iron
Diameter of bore	11·936
Polar angle	135°
Total height of limbs	30
Breadth parallel to shaft	15
Thickness of limb	5·75
Breadth of yoke	17
Depth „	6
Distance between centres of limbs	12·25
No. of turns shunt winding	3058
„ layers per limb	11
„ wires per layer	139
Diameter of wire, bare	0·065
„ „ „ insulated	0·08
Section „ „	0·0033
Resistance at 50° C.	30·1
No. of turns series winding	23
„ „ per limb	23

Dimensions of conductor, bare .	2 (0·48 × 0·13)
„ „ „ insulated	2 (0·51 × 0·16)
Section of conductor	0·1248
Resistance at 50° C.	0·0079

As can be seen from the drawings, the field-limbs consist of two rectangular slabs of (machined) wrought-iron, without separate pole-pieces, the polar-horns consisting of two strips of wrought-iron screwed to the limbs. The yoke consists partly of the bed-plate, but principally of a slab of wrought-iron bolted underneath. The shunt winding on each limb is connected in series, but the series coils are in two parallels, as indicated in the schedule above. Each armature bar is formed of two rectangular copper strips of the dimensions given above, laid together, double cotton-covered, braided, and varnished.

We will now proceed to analyse the design of this machine just as has been done for the others. The first thing to do is to construct the no-load characteristic. From the fundamental equation for the induced electromotive-force we have

$$E = \frac{780}{60} \times 120 \times N_a \times \frac{1}{10^8}$$

$$E = 0·0000156 \times N_a.$$

It is not necessary to work out more than two points of the curve in detail for this example, as the reader will be by this time sufficiently familiar with the process of calculation. Let us take, then, two points above and below the full-load values; thus

$$E = 90\text{; and } E = 115.$$

Then the corresponding armature fluxes are

$$N_a = 5,760,000\text{; and } N_a = 7,360,000.$$

A reference to the table of leakage coefficients (p. 137) tells us that for machines of this type and of approximately the same size

$$\nu = 1·28.$$

Hence to obtain the two armature-fluxes above, we have

$$N_{ii} = 7{,}390{,}000\,; \text{ and } N_{iii} = 9{,}430{,}000.$$

From the drawings we obtain

Length of mean path in armature-core = 5·5.
" " " two magnet-limbs = 46.
" " " yoke = 7.
" two air-gaps = 0·875.

And for the magnetic areas

Area of iron in armature-core = 4·75 × 13·125 = 62·5.
" " magnet-limbs = 5·75 × 15 = 86·3.
" " yoke = 6 × 17 = 102.

In accordance with the rules given on p. 144 we find the area of the air-gap as given below. But as the armature is somewhat longer than the pole-face, we must for this purpose consider the length of the latter as being the same as the gross length of the armature. Hence we have

$$\text{Magnetic area of pole-face} = \left(11{\cdot}936 \times 3{\cdot}14 \times \frac{135}{360}\right) \times 16$$

$$= 225 \text{ square inches.}$$

The area of the strip to be added on to this will not be less than

$$0{\cdot}437\left\{30 + 2\left(11{\cdot}936 \times 3{\cdot}14 \times \frac{135}{360}\right)\right\}$$

$$= 25{\cdot}4 \text{ square inches.}$$

So that the magnetic area of the air-gap may be taken as 250 square inches.

We can now fill in the two tables below for E = 90 and E = 115. The values of ampere-turns per inch (δ) have been taken from the respective curves of Plate I., and the air-gap ampere-turns calculated from the formula on p. 143.

$E = 90$; $N_a = 5,760,000$; $N_M = 7,390,000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-density.	Value of δ (from Curve).	Ampere-turns.
Yoke . .	Wrought-iron	7	102	72,400	16·8	119
Two limbs .	,, ,,	46	86·3	83,500	25·5	1172
Two air-gaps	Air	0·875	250	23,000	[0·3133]	6300
Armature core	Iron stampings	5·5	62·5	92,000	17·6	97
					Total ampere-turns =	7688

$E = 115$; $N_a = 7,360,000$; $N_m = 9,430,000$.

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-density.	Value of δ (from Curve).	Ampere-turns.
Yoke . .	Wrought-iron	7	102	92,500	41	287
Two limbs .	,, ,,	46	86·3	109,200	15·5	7140
Two air-gaps	Air, copper and cotton	0·875	250	29,400	[0·3133]	8060
Armature core	Iron stampings	5·5	62·5	117,500	22 0	1210
					Total ampere-turns =	16,697

In just the same way we find a few other points on the curve, obtaining thus

E = 105, Ampere-turns = 10950.
E = 100 ,, ,, = 9600.
E = 80 ,, ,, = 6350.
E = 60 ,, ,, = 4400.

Plotting the six points obtained in this manner, we obtain the no-load characteristic of the machine, as shown in Fig. 406. The necessary ampere-turns at no-load are then given by $X_1 = 10,950$, and these have to be provided by the shunt winding. At full-load the electromotive-force induced in the armature must exceed that at no-load by an amount sufficient to cover the ohmic drop in the armature winding and series

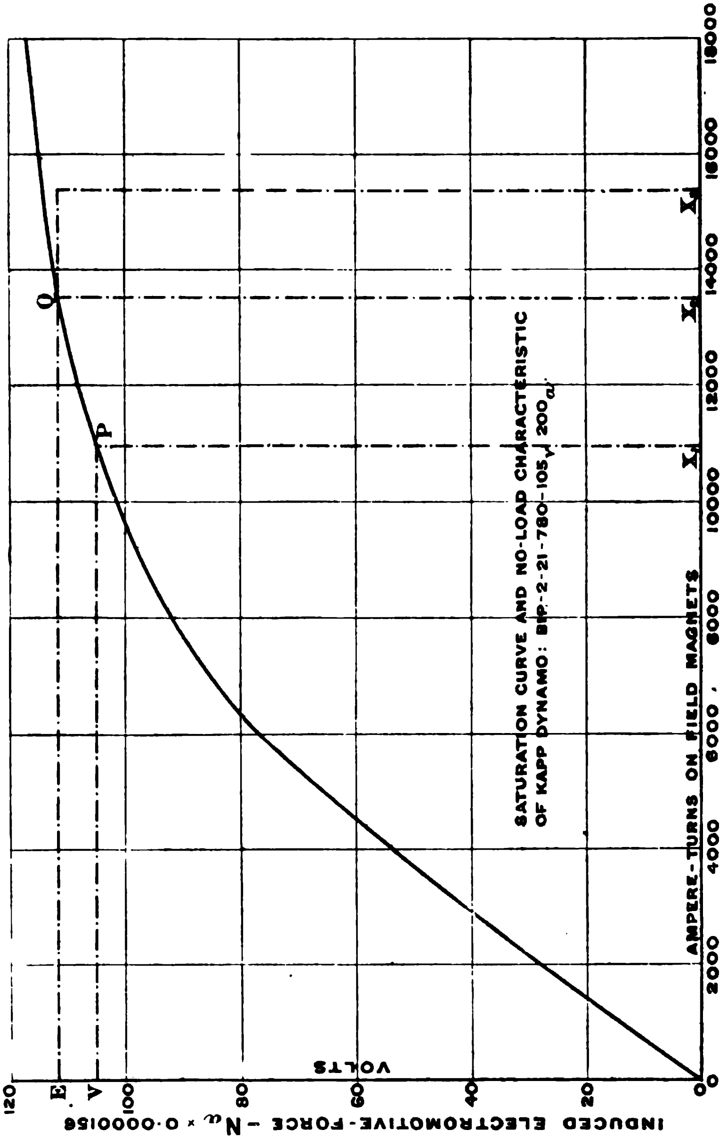


Fig. 406.—Kapp Bipolar 21 kw. Generator.

coils. The resistance of the whole armature winding at 50° C. is given by

$$r = \frac{9\cdot2 \times \text{total length of conductor}}{10^6 \times \text{section of conductor}}$$

$$= \frac{9\cdot2 \times 8\cdot32 \times 60}{10^6 \times 0\cdot046}$$

$$= 0\cdot0987.$$

Hence, neglecting the contact resistance of the brushes, as being unimportant in comparison in such a small machine, we have

$$r_a = \frac{0\cdot0987}{4} = 0\cdot0248$$

$$\text{practically} = 0\cdot025.$$

Adding this to the (hot) resistance of the series coils as given above, and multiplying by the full-load current, we have the lost volts at full-load as

$$e = 200 \times (0\cdot033) = 6\cdot6 \text{ volts.}$$

Thus at full-load the total induced electromotive-force must be

$$E = 105 + 6\cdot6 = 111\cdot6.$$

Projecting this value on the scale of ordinates across to the curve, we obtain X_2 as the corresponding value of ampere-turns necessary to produce it, if the brushes were always on the neutral diameter. This will not be the case, the brushes being under the pole-tips at full-load. The angle subtended by the pole-tips is (180 − 135) = 45°. Hence the conductors lying in this angle are

$$120 \times \frac{45}{360} = 15.$$

Therefore, as each carries 100 amperes (neglecting the small amount of current wanted for the shunt), we have as the demagnetizing ampere-turns of the armature

$$15 \times 100 = 1500.$$

These have to be compensated for on the field system, whose leakage coefficient is 1·28. Hence we obtain

$$1500 \times 1 \cdot 28 = 1920$$

compensating ampere-turns. Adding this number to X_2 we obtain X_3 as the necessary ampere-turns at full-load. From Fig. 406 we have

$$X_3 = 15{,}350$$

as the ampere-turns that have to be provided by the combined shunt and series winding. From the data given in the schedule we are enabled to compare our calculated values with those actually on the machine. The comparison is made in tabular form below.

Winding.	Calculated Values.	Observed Values.
Shunt ampere-turns .	10,950	10,670
Series " " .	4,400	4,600
Total " " .	15,350	15,270

With this compound winding the machine regulates very exactly.

We will now proceed to calculate the efficiency and heating of the machine. As it is for lighting purposes, the maximum efficiency would probably be arranged to occur at about three-quarter load, so we will make the efficiency calculate for this. The losses are as follows:—

(1) *Copper-loss.* The total resistance of the armature and series-winding is, as we have seen, 0·033 ohms hot. The copper-loss at three-quarter load is hence

$$150 \times 150 \times 0 \cdot 033 = 745 \text{ watts.}$$

(2) *The excitation-loss* in the shunt coils is given by

$$\frac{105 \times 105}{30 \cdot 1} = 366 \text{ watts.}$$

(3) *Iron-loss.* To calculate this we must first estimate the weight of iron. This is

$$\left\{\left(\frac{11\cdot0625 + 6\cdot312}{2} \times 3\cdot1416\right) \times 31\cdot25\right\} \times 0\cdot28$$

$$= 240 \text{ lbs. (with sufficient accuracy).}$$

Also the frequency of reversal is

$$\frac{780}{60} = 13 \text{ periods per second;}$$

and it is worked at three-quarter load at a flux-density of about 113,000 lines to the square inch.

Now from the curves in Fig. 54 we see that at a frequency of 30 ~ the hysteresis-loss per pound of iron when worked at 80,000 lines per square inch is about 2·1 watts, and the eddy-current loss under the same conditions is 0·8 watt. Hence the hysteresis-loss in this machine will be about

$$240\left\{2\cdot1 \times \frac{13}{30} \times \frac{(113{,}000)^{1\cdot6}}{(80{,}000)^{1\cdot6}}\right\}$$

$$= 240 \times 1\cdot58 = 380 \text{ watts.}$$

And the eddy-current loss will be

$$240\left\{0\cdot8 \times \frac{(13)^2}{(30)^2} \times \frac{(113{,}000)^2}{(80{,}000)^2}\right\}$$

$$= 240 \times 0\cdot3 = 72 \text{ watts.}$$

Hence the total iron-loss in the armature

$$= 380 + 72 = 452 \text{ watts.}$$

(4) *The friction, ventilation, and commutator losses* will be about 2 per cent. of the full-load output, that is

$$\frac{21{,}000 \times 2}{100} = 420 \text{ watts.}$$

Adding up the separate losses, we find the total losses of the machine running at three-quarter load to be about 1980 watts. Consequently the efficiency at this output is

$$\frac{15{,}750}{17{,}730} = 89 \text{ per cent.}$$

This figure is probably somewhat too low, in which case the difference would most likely be due to an over-estimation of the iron-losses.

We will now estimate the probable temperature-rise at full-load.

(*a*) Armature. The iron-loss will be about the same as that calculated above, namely, 452 watts, and the copper-loss is 200 × 200 × 0·025 or 1000 watts, making a total armature-loss of about

$$w'_a = 1450 \text{ watts.}$$

From the drawings we find the radiating surface to be about 890 square inches. Thus the watts per square inch radiating surface are

$$\frac{1450}{890} = 1 \cdot 63.$$

Referring to the lower curve of Fig. 99, p. 187, we see that at a peripheral speed of 2380 feet per minute there will be a probable temperature-rise of 27° C. We take the lower curve because the armature of this machine is very well provided with ventilating ducts (see Plate III.). The temperature rise is therefore likely to be

$$\theta_a = 27 \times 1 \cdot 63 = 44^\circ \text{ C.}$$

With regard to the field-coils, we know that the energy wasted in them at full-load is

$$369 + (200 \times 200 \times \cdot 0079) = 682 \text{ watts.}$$

From the drawings the heat-radiating surface is estimated as about 1400 square inches. The probable temperature-rise is therefore

$$\theta_m = \frac{682}{1400} \times 75 = 36 \cdot 5^\circ \text{ C.}$$

As this machine carries its full-load quite sparklessly when the brushes have the correct lead, it will be of interest to see now how nearly the design complies with the conditions for sparkless operation as given by our empirical formulæ. The number of cross ampere-turns at full-load are

$$X_c = \frac{135}{360} \times 120 \times 100 = 4500.$$

The ampere-turns for the air-gap at full-load are 7850, the flux-density being 28,600 lines per square inch. Hence the flux-density at the hindward pole-horn is approximately

$$28{,}600 \times \frac{7850 - 4500}{7850} = 12{,}200;$$

a value somewhat lower than that given as being the minimum for sparkless collection.

Tested by the two empirical *criteria* of sparking given on p. 278, we have these data :—

B_3 = 28,600 lines per square inch.
d' = 11·62 diameter of armature.
K = 60 total segments of commutator.
k_2 = 2, number of segments of commutator short-circuited at once.
g = 0·436 from iron to iron.
q_1 = $120 \times 100 \div 11{\cdot}62\,\pi$ = 328 ampere-conductors per inch at full-load.

whence we get

$$Y_1 = 28{,}600 \times 2 \div 328 = 174.$$
$$Y_2 = 60 \times 0{\cdot}436 \div 11{\cdot}62\,(1 + 2) = 0{\cdot}75.$$

Now for this class of machine (see p. 278) the conditions of non-sparking are that Y_1 should not be less than 23, and Y_2 not less than 0·6. Judging then from the design this machine ought to run sparklessly: as in fact it does.

The *stiffness ratio* (p. 277) comes out at 87, and the *commutation ratio* at 49, which is very satisfactory.

Example V.

COMPOUND MULTIPOLAR TRACTION GENERATOR,

MP 16—1000—90—500 volts—2000 amperes.

Designed by H. M. Hobart, constructed by the Union Elektricitäts Gesellschaft of Berlin, for the Sheffield Corporation.

This is an example of a slow-speed direct-driven generator. The construction is described in the *Elektrotechnische Zeitschrift*, xxiii. p. 44, Jan. 16, 1902. The design is amongst the machines described by Hobart in *Journ. Instit. Electrical Engineers*, xxxi. p. 170, and is further discussed by him in the *Elektrotechnische Zeitschrift*, xxii. p. 660, Aug. 15, 1901. In order to make this example as useful as possible it is here treated as though it had to be designed from the beginning; and the dimensions and calculations are in this instance given according to the metric system.

Prescribed Design.—To design a traction generator to give, at 90 revolutions per minute, 2000 amperes at 500 volts, the full-load efficiency being 94 per cent. Permissible temperature-rise 50° C. above surroundings at normal load in continuous use. To be able to stand a 25 per cent. overload for 30 minutes, and a momentary overload of 50 per cent. without harmful sparking or heating. The position of brushes to remain unchanged under all conditions.

1. *Determination of Trial Values for Armature Dimensions.*—This being a 1000 kilowatt machine, we may consider as a suitable peripheral speed (p. 536) 16 to 19 metres per second. To apply Esson's formula, [III.] p. 542, we assign the following values: $B_g = 8600$; $q_1 = 260$ amps. per cm.; $\psi = 0{\cdot}72$. From these by equation [IV*b*] p. 543, we get:—

$$\kappa = \frac{60{\cdot}8 \times 10^{10}}{8600 \times 260 \times 0{\cdot}72} = 380{,}000.$$

Inserting this value in equation [IV*a*] we obtain:—

$$d^2 l = 380,000 \times \frac{1000}{90} = 4,210,000.$$

Constructing a table of a few trial values of d and l to fit this product, and adding the corresponding peripheral speeds, we have:—

d	l	$d^2 l$	metres per second
250	67·4	421,000	11·8
300	47	,,	14·1
350	34·4	,,	16·5
400	26·3	,,	18·88
450	20·7	,,	21·24

We select, as not giving too high a surface speed, the third value, where $d = 350$ cm. and $l = 34·4$, or, say 35 cm., making the ratio of l to d exactly 1 to 10.

2. *Number of poles.*—As the full-load current is 2000 amperes we cannot well have fewer than 16 poles; for, assuming a lap-winding with 16 circuits we shall have 250 amperes to collect at each brush-set. For an economical design 16 poles should suffice.

3. *Pole-face.*—The periphery will be $350 \times \pi = 1100$, and the pole-pitch therefore about 68 cm. The equivalent pole arc is 72 per cent. of this or 49 cm.; so that the pole-face will be about $49 \times 35 = 1715$ square cm.

4. *Flux from one pole.*—At the assumed density of 8600 the provisional value of the flux will be $1715 \times 8600 = 14,749,000$ lines.

5. *Armature Conductors.*—At 90 revs. per minute, $n = 90 \div 60 = 1·5$ revs. per second. Therefore, if E be 500 volts we find by the usual formula:—

$$Z = E \times 10^8 \div n N$$

$$Z = (500 \times 10^8) \div (1·5 \times 14,749,000)$$

$$= 2258.$$

But for lap-windings, especially if equalizing rings are to be added, it is preferable that Z should be an even multiple of the number of poles. Now 2258 is not divisible by 16, and therefore must be adjusted. As we have taken E at 500 volts, allowing nothing for any internal drop, it will be safer to increase Z than to diminish it. We will therefore take Z as $144 \times 16 = 2304$. This will reduce **N** to about 14,500,000.

6. *Check results so far.*—As there are 8 pairs of poles, and $n = 1 \cdot 5$, the frequency of the cycles of magnetization will be 12, which is not too high. Further, as there are 16 paths, each circuit of the armature will carry 125 amperes; and the number of ampere-conductors per centimetre will therefore be $125 \times 2304 \div 1100 = 262$, which is not too much above the assumed value to be unsafe.

7. *Commutator Segments.*—Taking one loop per segment of the commutator will make $K = 2304 \div 2 = 1152$. This gives 72 loops per pole; with an average voltage per loop of $500 \div 72 = 6 \cdot 95$. Testing by Arnold's rule (p. 483):—

K must not be less than $0 \cdot 037 \times 2304 \times \sqrt{125} = 956$.

Thus the number 1152 is satisfactory.

8. *Size of Commutator.*—The peripheral speed should be about 13 metres per second; and the breadth of a segment should not be less if possible than 7 mm. Now the former datum at 1½ revolutions per second would give a periphery of $13 \times 100 \div 1 \cdot 5 = 8666$ mm.; and the latter gives $1152 \times 7 = 8064$ mm. We will take 8500, making the diameter 2700 mm., the peripheral speed 12·7 metres per second, and the gross width of segment 7·4 mm. Allowing 0·76 mm. for mica insulation, makes the nett width 6·64 mm. To collect 250 amperes at 5 amperes per square cm., will demand 50 square cm. of brush contact surface. The brush cannot well be more than 2 cm. broad, nearly covering 3 segments; but its effective width is less by the amount of two thicknesses of mica. Taking the effective width as 1·85 cm., there will therefore be required a nett length of $50 \div 1 \cdot 85 = 27$ cm., and allowing 7 cm. for space between brushes and 4 cm. for a margin at the ends will make the commutator 38 cm. long. The peripheral cooling surface of the commutator will therefore be $270 \times 38 \times \pi = 32{,}700$ square cm.

9. *Gross Length and Cooling Surface of Armature.*—The

style is a barrel-winding. Estimating the length to which the oblique parts stand out at the ends as 0·325 of the pole-pitch we have for the length over all:—

$$35 + 2\,(68{\cdot}8 \times 0{\cdot}325) = 80 \text{ cm.}$$

As the periphery is 1100 cm. we have 88,000 sq. cm. or 880 sq. decim. of cylindrical surface.

10. *Assignment of Losses.*—We assume the copper-loss in the armature to be 2·5 per cent. of the full-load output, and the iron-loss about 1·75 per cent., in total 4·25 per cent., that is 42,500 watts in the armature. The commutator-losses we put at 0·75 per cent., or 7500 watts; the excitation-losses at 1·25 per cent., or 12,500 watts.

11. *Probable Heating of Armature.*—According to Hobart,[1] with large armatures of such proportions, and well ventilated, there will be a temperature-rise of from 0·7 to 1·0 deg. Centig. for every watt lost per square decimetre of total cylindrical armature surface. As this armature is to be exceptionally well ventilated the lower figure may be taken. The number of watts per square decimetre is 42,500 ÷ 880 = 48·3; hence the probable temperature rise will be 48·3 × 0·7 = 33·8 deg. Centig.

12. *Armature Conductors.*—Assuming a current-density not exceeding 3 amp. per sq. mm., the appropriate conductor to carry 125 amp. will be one with at least 42 sq. mm. section. But in view of over-load requirements it is well to take the section a trifle larger. If we take 2·9 amp. per sq. mm. the section may be enlarged to 43·2 sq. mm. In order on the one hand to secure space for insulation, and on the other to get high saturation in the teeth, we will assume that 6 conductors are placed in 1 slot. This makes the total section of copper in 1 slot as 43·2 × 6 = 259 sq. mm. The mean length of one turn will be about 275 cm.: hence the total length of copper conductor 316,800 cm. The total volume of armature copper will be 136,752 cub. cm., and its total weight about 990 kg.

13. *Armature Slots.*—The total section of copper in one slot being 259 sq. mm., and experience showing that in

---

[1] *Elektrot. Zeitschr.*, xxii. p. 652, Aug. 15, 1901.

machines of this type a space-factor of 0·515 can[1] be attained, the slot area will be 259 ÷ 0·515 = 503 square mm. The number of slots will be 2304 ÷ 6 = 384; and as the periphery is 11,000 mm., the slot-pitch at the armature-face will be 11,000 ÷ 384 = 28·6 mm. The flux-density in the gap is 8600; but it ought to be at least 25,000 (apparent) in the teeth. Now, owing to the air-ducts and insulation between the core-disks, the effective length of iron will be only about 24 cm. as compared with the gross length of 35 cm. This of itself would increase the density to 12,500; but if the apparent density is to reach 25,000, it is clear that the section must be at least halved. In other words, the slots must be at least as broad as the teeth—preferably a little broader. Take then as breadth of slot 14·8 mm., leaving 13·8 as the breadth of tooth at the face. Then the depth of slot will be 503 ÷ 14·8 = 34 mm., which is a reasonable depth; though when the 6 conductors are arranged with their insulation it may be needful to revise the precise dimensions.

14. *Arrangement of Conductors in the Slot.*—For barrel-winding the 6 conductors must be arranged two deep, therefore three side by side. A suitable insulation thickness for machines of this class is: 1·3 mm. between the iron teeth and the conductors, and 0·4 mm. as a thin taping round each conductor in the slot. (Projecting end parts require a second protective taping.) This makes the thickness x of the copper conductors such that $3x + (6 \times 0{\cdot}4) + (2 \times 1{\cdot}3) = 14{\cdot}8$. Then $x = 3{\cdot}26$ mm.; but as the fit must not be too tight, otherwise the insulation may be damaged in forcing the conductors into the slot, let us say 3·2 mm. As the section of copper of each conductor has to be 43·2 square mm., the depth of the copper conductor must be 43·2 ÷ 3·2 = 13·5 mm. The taped conductors, 2 deep, will measure $(2 \times 13{\cdot}5) + (4 \times 0{\cdot}4) = 28{\cdot}6$ mm. To this add for slot-lining and an inserted strip between the upper and lower set 3·9 mm., and 1·5 more for packing. This makes the slot

---

[1] Note: an unusually high space-factor for 500-volt machines, and one impossible of attainment except by grouping several conductors in a slot, and by using fine insulation.

depth 34 mm. By this arrangement the dimensions provisionally adopted above are found adequate, though there would have been some advantage in allowing a deeper slot for more packing.

14. *Internal Diameter of Core.*—The pole-arc being 49 cm., a trial value for the core is half this (viz. 24·5 cm.), seeing that it must carry half the flux. But as the nett length of iron in the core is only 0·68 of the gross length (owing to ducts and insulation), this would force up the flux-density to 8600 ÷ 0·68 = 12,600, which is too high for core-disks. The density ought not to exceed 10,000. We will therefore take the core-depth as 24·5 × 12,600 ÷ 10,000 = 31·1. Doubling this and adding twice the length of the tooth, and deducting from 350 gives 281 for the internal diameter.

15. *Flux-Density in Teeth.*—At this stage we ought to test the density in the teeth. They are 13·8 mm. wide at the face. They will be, it is true, slightly narrower at the root. But on an armature so large as this any error introduced into the calculation by assuming them to be of parallel form may be set against the opposite and greater error involved in the assumption that the flux-density in the slots is negligibly small. Now the flux entering the armature per pole is 14,750,000 lines, and the number of teeth under one pole, allowing one tooth at each side for fringing, is 19. Taking the nett iron length at 23·6 cm., the nett sectional area of iron in the teeth under 1 pole will be 19 × 1·38 × 23·6 = 595 square cm.; and the apparent density in the teeth will be 14,750,000 ÷ 595 = 24,800. This density, though certainly high, is not too high for such a well ventilated core; and it may be remembered that the magnetic frequency of reversal is only 12 cycles per second.

16. *Air-gap.*—As the slots are 14·8 mm. wide, the least possible length of air-gap is two-thirds of this, or 9·89 mm. Of other rules the simplest is to make the length (in cm.) = 0·88 × $d\,l \div K$; i.e. 0·88 × 350 × 35 ÷ 1152 = 0·93, or 9·3 mm. Or by equation [X*c*], p. 551, 9·86. We will take 10 mm. as the nearest integer. It is $\frac{1}{49}$ of the pole-span.

17. *Length of Pole-Core.*—As a trial value 40 times the

length of the air-gap is usual for compound machines. As the densities are all very high in this machine it will be safer to allow more, say 48 cm.

18. *Section of Pole-Core.*—The no-load useful flux per pole being 14,750,000, and the full-load useful flux being 14,900,000, with a dispersion co-efficient of 1·125, we have for the full-load flux in the pole 16,800,000. To carry this, if the permissible density in the pole-core of mild steel be about 15,000 lines per square cm., there will be required a sectional area of about 1130 square cm. A circular core 38 cm. in diameter will meet the requirement.

19. *Size of Yoke.*—Allowing 3 cm. for the thickness of the pole-shoe, the inner diameter of the yoke becomes 350 + 2 + 6 + 100 = 458 cm. If the breadth is chosen at 70 cm. so as to protect the flanges of the coils, the depth radially must be determined from the necessary section. It must carry about 8,400,000 lines, and if of cast-iron, the appropriate density is 4000. Hence its section should be 2100 square cm. It must therefore have an average depth of 30 cm. A suitable form of section is one with two stiffening ribs ; and taking the usual design, these will contain nearly half the metal, and will stand about 24 cm. higher than the outer periphery of the yoke, and about 36 cm. from the inner periphery. This will make the over-all diameter 458 + 76 = 534 cm.

20. At this stage it will be expedient to make the first drawing in order to proceed with the real computation of the machine. From the drawings the excitation must be calculated, as for the preceding machines, at several different voltages, and the saturation curve or no-load characteristic drawn. The various losses must be ascertained, the corresponding temperature rises estimated, and the efficiency calculated for various loads. If need be, the dimensions of the machine should be modified, and the calculations gone over again.

As a matter of fact, though the machine as designed had the dimensions here assigned, there were some small alterations made in the construction in the works, and of these the most important was the increase of the air-gap from 10 mm. to

13 mm. Mr. Hobart gave the following data as to the design :—

Ampere-turns per magnet-pole,	no-load, at full-load voltage .	11,000
,, ,, ,,	full-load ,, ,, .	14,000
,, ,, ,,	to balance armature-reaction .	3,000

Losses and efficiency, at 60° C. :-	Watts.	Percentage of Full-load Loss.	Percentage of Output.
Armature iron loss	18,000	2·90	1·8
Armature copper loss	24,000	3·88	2·4
Commutator brush contact loss . .	4,400	0·72	0·44
Commutator friction loss . . .	2,800	0·45	0·28
Commutator miscellaneous losses . .	200	0·03	0·02
Loss in shunt winding	8,250	1·33	0·825
Loss in series winding	2,250	0·37	0·225
Loss in shunt regulating rheostat . .	1,250	0·20	0·125
Loss in series bye-pass coil . . .	750	0·12	0·075
Total of the constant losses . . .	30,500	..	..
Total of the variable losses, at full-load .	31,600	..	..
Total of all losses, at full-load . .	62,100	100	6·21

Commercial efficiency at full-load (per cent.)	94·1
,, ,, at ¾ load ,, ...	94·0
,, ,, at ½ load ,, ...	92·9
,, ,, at ¼ load ,, ...	88·5
Watts lost per square decimetre armature peripheral surface .	48
,, ,, ,, commutator ,, ,, .	25
,, ,, ,, magnet ,, ,, .	9

Weights (in kilogrammes) : armature laminations 5300; armature copper 900; commutator segments 1700; magnet copper 1570; pole-shoes 1000; pole-cores 7000; yoke, total including feet, 27,000. Total weight without the shaft 62,000. Total cost of effective material, 19,500 marks.

The Figs. 407 to 414 depict the drawings of this machine as described by Dr. Niethammer. The cast-steel poles are secured to the yoke by two screws each. The yoke stands on two feet each provided with two adjusting screws which press on a foot-plate. At its lowest point the yoke is also supported on an adjustable block. The magnet bobbins are of sheet iron with flanges of malleable iron. The shunt-winding consists of 640 turns per pole, of a round wire 4·5 mm. in diameter. The series-winding is of 2½ turns per pole of flat copper strip,

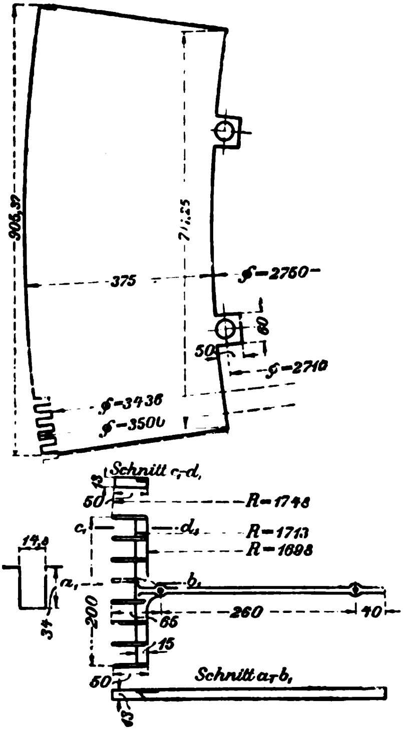


FIG. 407.—CORE SEGMENT AND VENTILATING-PIECE.

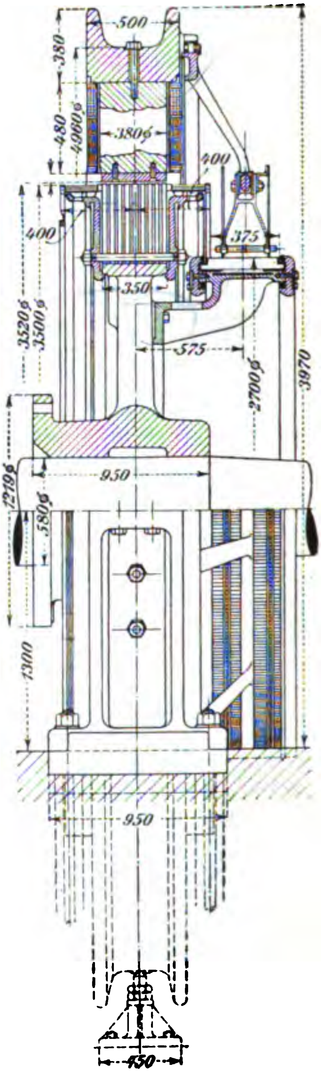


FIG. 409.—LONGITUDINAL SECTION OF HOBART GENERATOR.

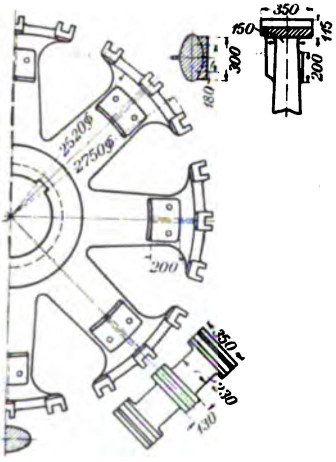


FIG. 408.

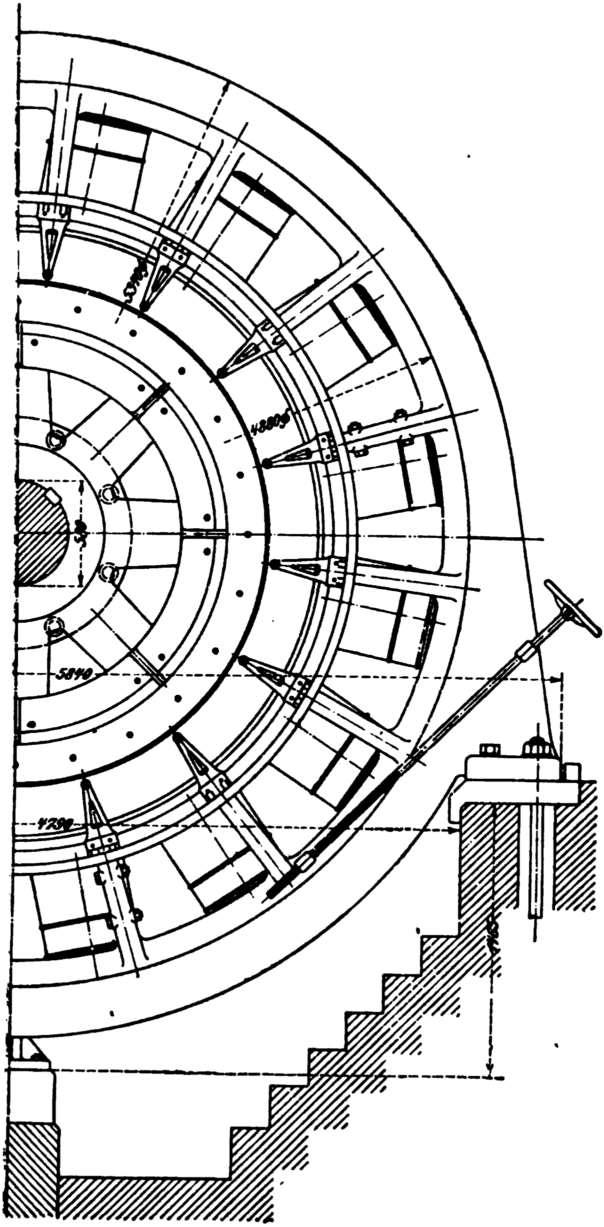


FIG. 410.—GENERAL VIEW OF HOBART'S GENERATOR, M P 16—1000—90.

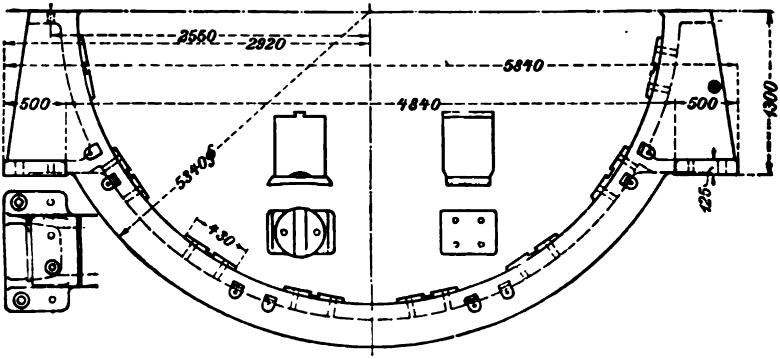


FIG. 411.—LOWER HALF OF YOKE, POLE-CORE, AND POLE-SHOES.

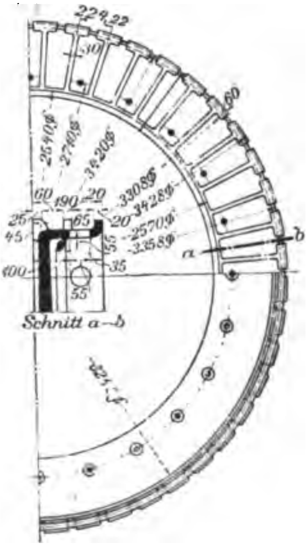


FIG. 412.—END CLAMPING PLATES FOR ARMATURE.

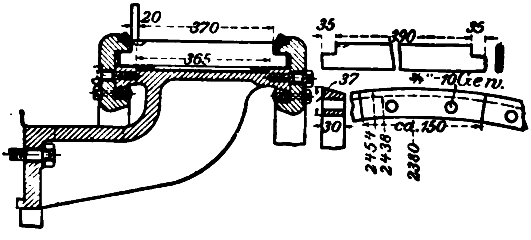


FIG. 413.—COMMUTATOR SECTION AND DETAILS.

1 mm. thick and 80 mm. wide. The core-stampings are in segments (Fig. 407), embracing $\frac{1}{12}$ circumference, with 32 slots in each. Bolts pass through the two lugs in each segment to fix them to the spider. A coating of asphaltum varnish serves as insulation. The ventilating pieces, Fig. 407, 13 mm. thick of cast-iron, are interposed at every 60 mm. or so. The end clamping rings, Fig. 412, are constructed with projecting rims to support the winding, and are cut away to form ventilating spaces. Binding wires are applied only over the projecting

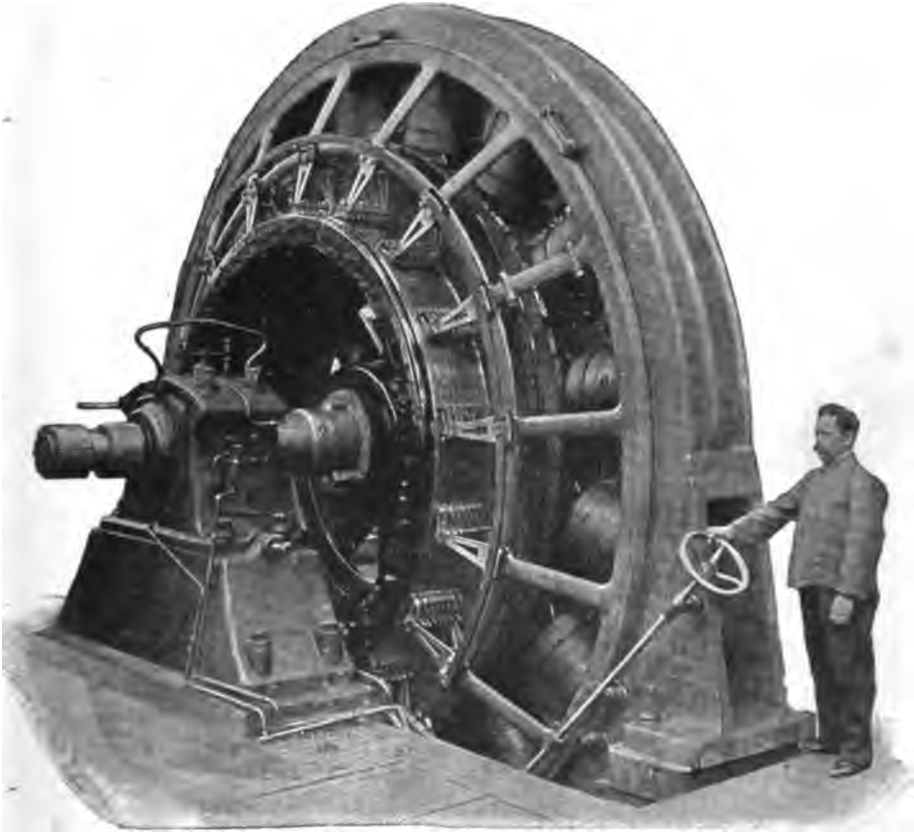


FIG. 414.—HOBART'S GENERATOR, MP 16—1000—90 (Union Elektricitäts Gesellschaft, Berlin).

ends of the winding. At the back of the armature are equalizing rings, eight in number. The commutator, the arrangements of which are shown in Fig. 413, is bolted to the spider-arms. The tightening is effected by conical steel rings, in segments, which are screwed up inside the steel clamping rings at the ends of the commutator. Two projecting rings of ambroin provide a secondary insulation at the limits of the commutator face. There are 16 rows of brushes, 8 brushes in each row, having each a contact-face 19 × 32 mm. Fig. 414 shows a completed view of the machine.

Example VI.

A SMALL GENERATOR.

(Adapted from a machine of Kolben & Co.)

The last example shall be an application to the design of a small machine, that it may be seen how readily the main features may be ascertained.

To design a 3-kw. Dynamo, running at 1100 *R.P.M., at* 120 *volts, overcompounded to give its full-load current of* 25 *amperes at* 123 *volts at terminals.*

In small machines there may be trouble if the ampere-density per inch of periphery is as high as is permissible in large machines. From 150 to 200 is usual; so provisionally we will take $q_1 = 175$ amperes per inch. The ratio of pole-arc to pole-pitch will be taken as 0·7. The pole-face density may be taken at 32,000 lines per square inch. By formula [III], p. 542, we then have

$$d^2 l = 60{\cdot}8 \times 10^{10} \times 3 \times \frac{1}{1100 \times 32{,}000 \times 175 \times 0{\cdot}7};$$
$$= 425.$$

Assuming the pole-face to be square we shall have

$$l = 0{\cdot}7 \times \frac{\pi d}{p}.$$

And if p be taken at 4, $l = d \times 0{\cdot}55$, whence

$$d^3 = 770;$$
$$d = 9{\cdot}15 \text{ or say } 9\tfrac{1}{8} \text{ inches};$$
$$l = 5{\cdot}0 \text{ inches.}$$

Then the armature circumference will be 28·7, and the pole-pitch at armature face 7·2. The pole-arc will be 70 per cent. of this, or 5 inches. The area of pole-face will be about 25 square inches, and the flux (provisionally) about 25 × 32,000 = 800,000.

This machine will be designed with certain features in common with those of modern tramway motors: that is to say, though it is a 4-pole machine, there will be only two sets of brushes; the armature coils shall be former-wound, and drop into the slots; the winding will therefore be a series-parallel one with only 2 paths; and for simplicity also of construction, though there are 4 poles, only two of these will be wound. Such an armature design necessitates an odd number of teeth and of commutator segments (see p. 466). We have obtained as a rough trial value for the full-load flux $N_a = 800{,}000$. As the terminal voltage at this load is 123, and as some 5 or 6 per cent. must be allowed for voltage-drop, we will make our calculations for 130 volts. Then since

$$E = \frac{p}{c} \times n \times Z \times N \div 10^8,$$

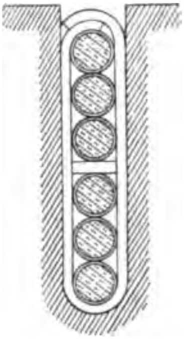
$$130 \times 10^8 = \frac{4}{2} \times \frac{1100}{60} \times Z \times 800{,}000;$$

$$\frac{130 \times 10^8 \times 60 \times 2}{4 \times 1100 \times 800{,}000} = Z = 443 \text{ provisionally.}$$

Now, as the conductors will have to be wound on formers in coils so as to have 2, 3, 4 or 6 turns in each coil, and as the number of wires in one slot must be either 4, 6, 8 or 12, we must select some suitable number, of slots, and of wires per slot, the product giving a final number for Z, preferably less than 443. Four wires per slot will involve too many teeth, and twelve per slot will give too few. For, as the periphery of the armature is 28·7 inches, 80 or 90 slots would be too many, while 30 is unduly few. We might take 51 slots with eight wires per slot (making Z = 408) or 69 slots with six wires per slot (making Z = 414). To guide our choice, consider the size of the wire required; and then see how such wires could be grouped six or eight together in a slot. There are two circuits through the armature, therefore each wire must carry 12·5 amperes. Allowing, say, 600 circular mils per ampere, a suitable cross-section would be 7500 circular mils. The nearest standard wire is, as the wire-gauge tables show, a No. 13 S.W.G. with diameter 0·092 inch, or a No. 12 B. and S. with a diameter of 0·081 inch. The diameters covered will be respectively 0·104 and 0·093. Taking the former wire we see that if six of them are put above one another in a slot lined with micanite to a thickness of 35 mils, the slot must be ·174 inch wide, and (allowing 0·2 inch extra for insulation between upper and lower coil, and for insulation at the top) at least 0·824 inch deep. If we try to put eight in a slot, they must be put in two fours, and the width with insulation must be at least 0·278 and the depth at least 0·756 inch. Assuming that the slot is about 0·4 of the tooth-pitch, we shall see that the former arrangement implies a tooth-pitch of 0·435 inch, and the latter implies one of 0·695 inch. As the periphery is 28·7 inches, the former gives room for 67 slots (i.e. 6 × 67 = 402 wires); the latter for 41 slots (i.e. 8 × 41 = 328 wires). The latter will not do, the former will; and the 67 slots might be increased to 69 without too much decreasing the width of the teeth; for 6 × 67 = 402 only, which is rather low; and 6 × 69 = 414 is better. In fact, with 69 slots the tooth-pitch will be 28·7 ÷ 69 = 0·416 inch, and the ratio of slot-width to tooth-pitch is 0·418, which is not too high. So we will take 69 slots with six conductors in each arranged as in Fig. 415, or in total 414 conductors. Having settled Z = 414 thus definitely we must now recalculate N.

$$\frac{130 \times 10^8 \times 60 \times 2}{4 \times 1100 \times 414} = 860,000$$

instead of 800,000. This makes the pole-face density 34,300 instead of 32,000; and the tooth-density will be 34,300 ÷ 0·418, about 82,000 at the tops, or about 91,500 having regard to the allowance of insulation between the laminations; making about 122,000 at the roots of the teeth.



Scale 2 : 1

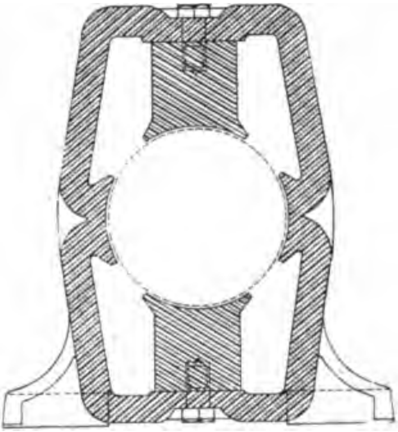
FIG. 415.

A suitable width of gap (see rules on p. 550) will be ⅛ inch or a little less, say 120 mils; the field-bore being 9¼ inches.

In this type of field-magnet the magnetic leakage will be higher than in the types that have all poles wound; the coefficient of dispersion may be put at 1·3, giving as the flux in the pole-cores at full-load about 1,120,000 lines. The ordinary calculation of the magnetic circuits (as on p. 148) will show that 4220 ampere-turns will be required at full-load for each pole-pair; and about 3520 at no-load. Therefore the shunt-winding, allowing a shunt-current of 1·6 amperes (i.e. 6·4 per cent. of full current), will consist of 2200, or with a small margin for regulation, 2300 turns; and the series-winding will need 700 ÷ 25 = 28 turns, on each pole. The armature coils, 69 in number, will each have three turns of wire, and will be joined in series as in Fig. 251, p. 402, and will span over 17 teeth.

At each brush-set there will be 25 amperes to collect; so that allowing 30 amperes per square inch of brush-face, a section of 0·86 square inch will suffice. Two "brushes," each 0·55 × 0·8 inch, put side by side at each of the two collecting places, will suffice. A suitable size of commutator will be 4 inches in diameter and 1·85 inch long in the face. There will be 69 segments, each 0·16 inch wide at the face, with mica slips 25 mils thick between them.

The total length of wire on the armature will be approximately 510 feet, and the resistance (hot) of the armature will be about 0·18 ohm, or, allowing 0·35 as the contact resistance at each brush-set, there will be a total internal resistance of about 0·25 ohm. There will be 14·4 wires per inch of periphery, and as each carries 12·5 amperes, the peripheral ampere-density will be 180 amperes per inch. The shunt-winding will consist suitably of 2300 turns of a wire having 1600 circular mils of section, that is a No. 19 S.W.G., measuring 40 mils bare, or 52 mils covered, on each of the two bobbins. As the mean length of one turn will be about 18·9 inches, the total length of wire for the two bobbins will be about 7225 feet, and its resistance (hot) will be about 50 ohms. At the voltage of 123, an auxiliary resistance of about 22 ohms will be needed in the rheostat. The series-winding has to carry 25 amperes, and will need a section of about 30,000 circular mils. A No. 7 S.W.G. wire of diameter 0·176 inch bare, and 0·190 covered, will suffice. The 28 turns on each bobbin will together require about 125 feet, with a resistance (hot) of about 0·05 ohm.

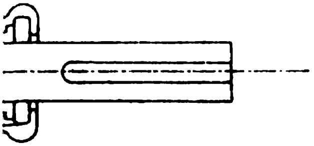


Scale 1 : 8

FIG. 416—3-KW. GENERATOR (KOLBEN'S PATTERN).

FIELD MAGNET.

8.



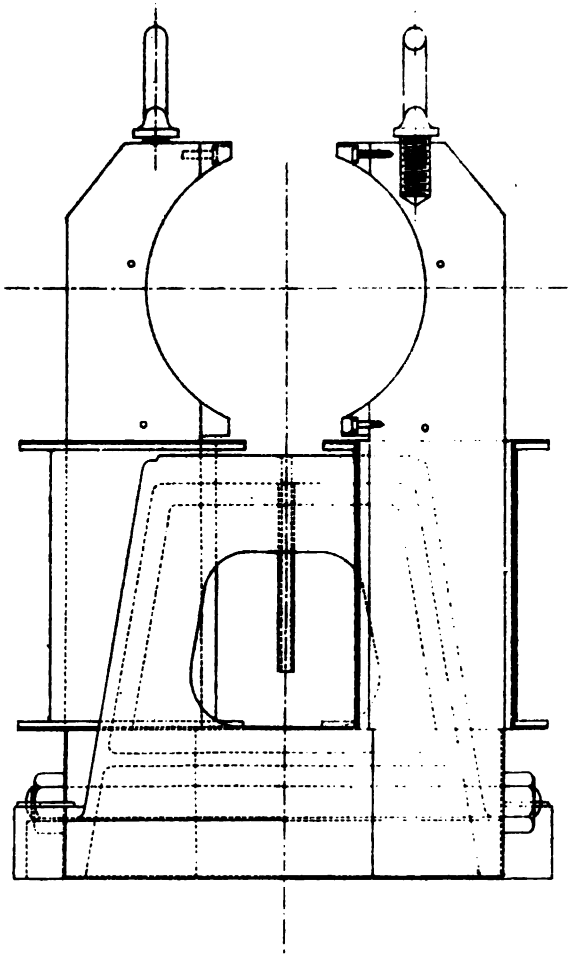
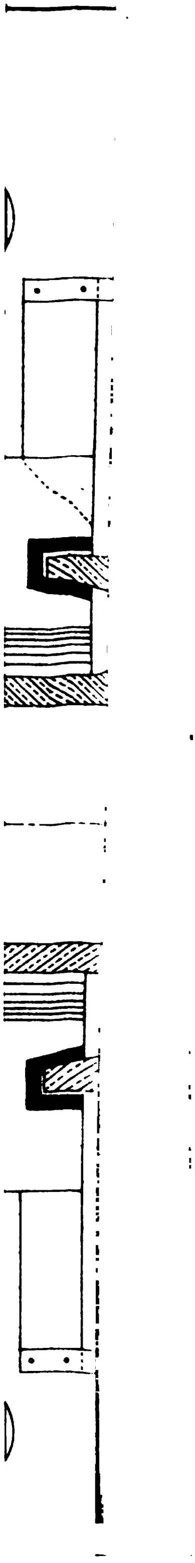
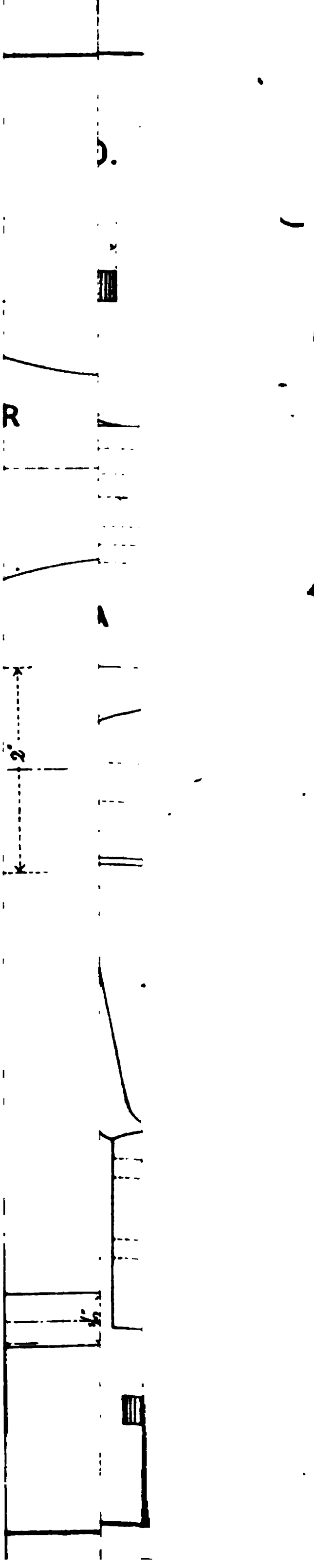


FIG 3.

Thos. Kell & Son, Lith.




R
2'

by first-rate firms being necessarily omitted for want of space. In former editions of this book many forms have been described that are now omitted. In the French edition of this work, translated by M. E. Boistel, a number of types prevalent in France are mentioned. The author naturally devotes space to notice chiefly those machines of which he is able to give detailed information or drawings, and acknowledges the courtesy of the various designers and manufacturers in enabling him so to do.

Kapp's Bipolar Generator. Plates II., III. and IV.—This machine, designed by Mr. Gisbert Kapp and built in 1887 by Messrs. Johnson and Phillips, is of the "over" type, with a smooth-core drum-armature. It is a 21-unit machine, giving 200 amperes at 105 volts at 780 revolutions per minute. The design has already been analysed in Chapter XIX. pp. 621 to 631.

One peculiarity in this dynamo is the mode of driving the conductors of the armature. As shown in the section in Plate III., there are introduced at intervals between the core-disks, some thicker disks having ventilating apertures and projecting horns of steel. Around these steel horns are placed pieces of hard white fibre, as driving-horns; and as these project in alternate positions, the copper conductors cannot be laid straight, but are given a sinuous form. Plate III. also shows how the core-disks are clamped together by face-plates having ventilating perforations through them, the whole core being held up against a collar on the shaft by a screw-nut. The figures in Plates II., III. and IV. also show the details of the brush-holder and rocker, the construction of the field-magnet, the arrangements of the bearings, and the pattern of lubricator employed.

For other types of generator designed by Mr. Kapp the reader is referred to his excellent work, *Elektromechanische Konstruktionen* (2nd edition, Berlin, 1902).

Oerlikon Co.'s Dynamos. — For many years past the Oerlikon Machine Works near Zürich have produced excellent machines. Till 1892 the chief designer was Mr. C. E. L. Brown. After that date Mr. Kolben and Dr. Behn

Eschenburg have successively been mainly responsible for the types produced. With the Oerlikon works originated the multipolar type of generator of which Fig. 417 is an example, a type which since 1890 has been extensively followed in the United States as well as in Great Britain.

Plate XV. shows an Oerlikon MP 4—265—370 machine. The general aspect is given in Fig. 418. Of this pattern a 450-volt generator is at work in the Central London Railway, and a 550-volt one at Zürich. Both machines are identical in all respects except as to the number of slots and conductors, corresponding to the different voltages.

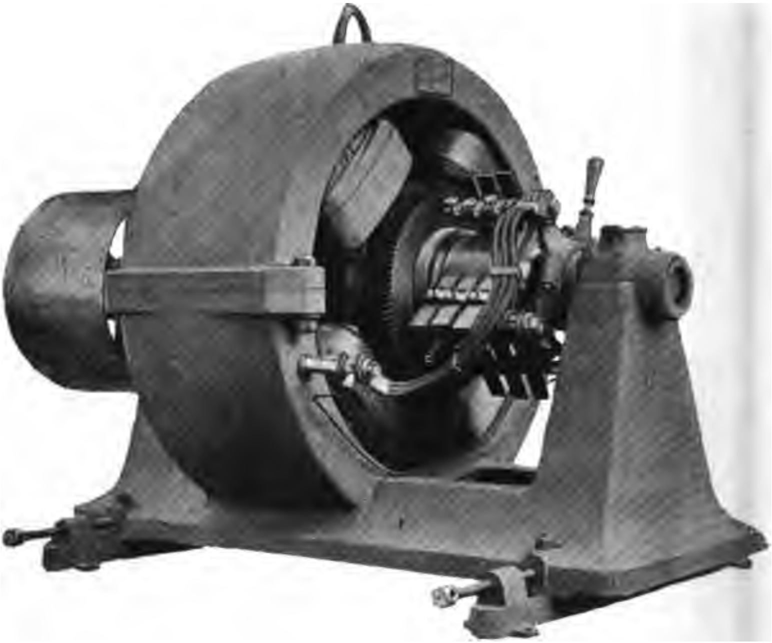


FIG. 417.—OERLIKON CO.'S 4-POLE 60-KW. DYNAMO (1895 type).

The yoke is of cast-steel, the diameter over yoke being 75 inches, and the length of yoke parallel to shaft is 17·3 inches. The four field-coils each have, in the 550-volt

NUOUS C

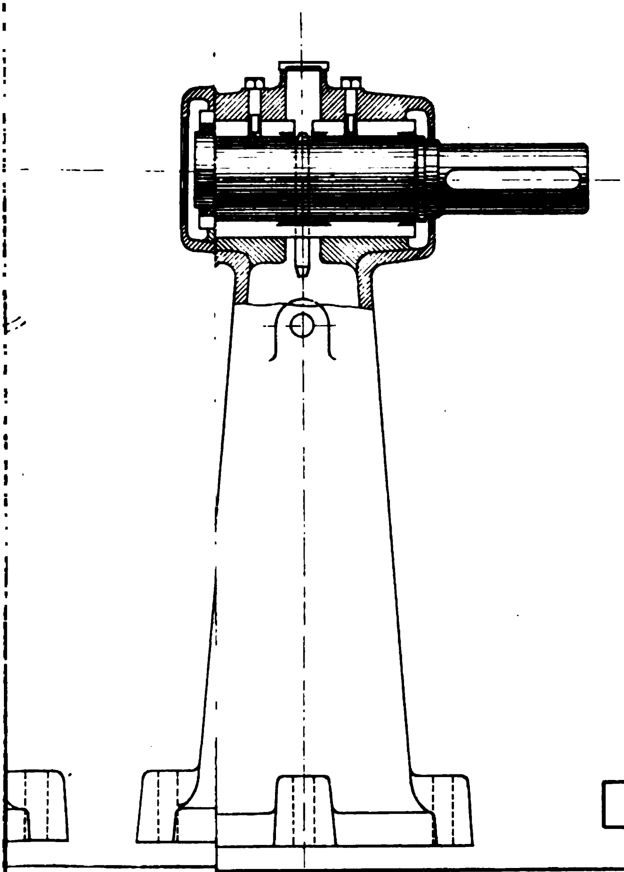
P 4-265-

P 4-265-

Construc

Oerlikon M

Scal



on Lᵈ London

Tho.ˢ Kell & Son Lith

machine 3200 turns, and in the 450-volt machine 2600 turns, the diameter of the shunt-wire in the former case being 0·079 inch, and in the latter 0·087 inch. The higher voltage machine, that is to say, the Zurich generator, is compounded, there being 3½ turns of strip copper conductor on each pole, this conductor measuring 0·138 inch by 6·75 inches insulated. The pole-pitch is 31·5 inches, the pole-pieces being rectangular, length parallel to shaft 19·3 inches, and pole-arc 23·6 inches. The length of air-gap in both machines is 0·49 inch. The diameter of armature is 39·4 inches, length over conductors 26·8 inches, and length between core-heads 19·7 inches ; there being one ventilating duct in the armature 0·98 inch wide.

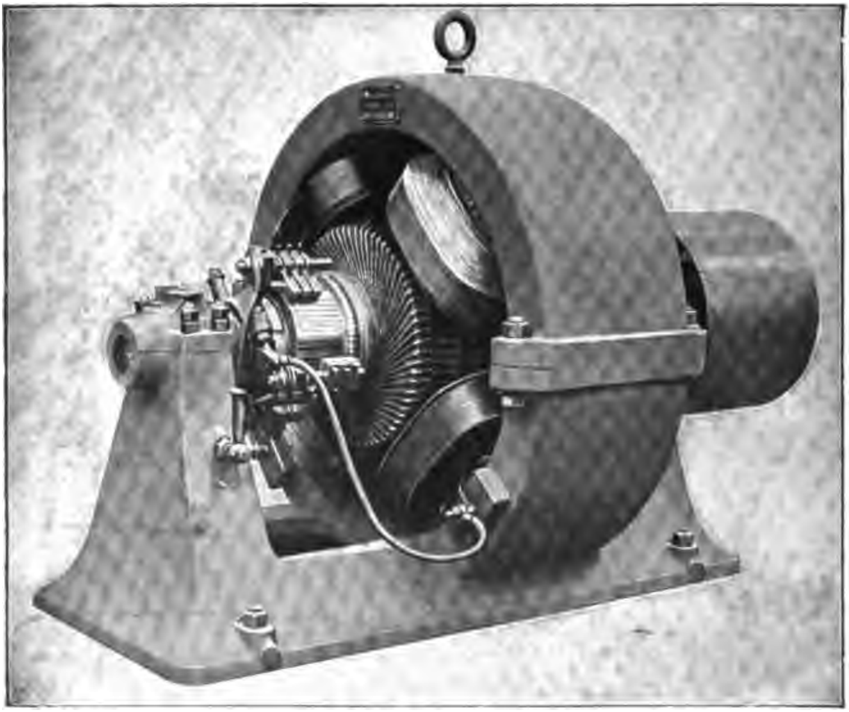


FIG. 418.—TYPICAL 4-POLE GENERATOR OF THE OERLIKON WORKS 1902).

The machine for Zurich has 240 slots and 480 conductors each 0·114 inch by 0·925 inch, the slots being 0·256 inch wide and 1·02 inch deep; and in the machine for London there are 208 slots and 416 conductors each 0·138 inch by 1·04 inch, the slots being 0·335 inch wide and 1·18 inch in depth. The winding in the Zürich machine is a four-circuit doubly re-entrant winding (symbol ◎) with four sets of brushes and four parallel paths through the armature. The London machine has a singly re-entrant lap-winding with four circuits in parallel. The commutator is 22·8 inches in diameter, there being 240 segments in the Zürich machine and 208 in the London machine, the length of segment being about 9 inches.

Plate XIX. shows an Oerlikon traction generator M P 12—500—100—550 volts—900 amperes. A general view of the machine is afforded by Fig. 419.

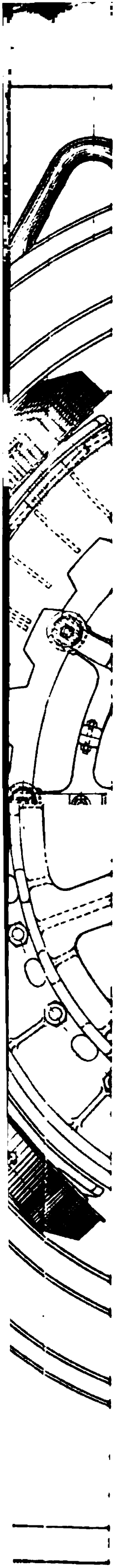
This machine, of which two were constructed for the Basel tramways, was required to fulfil somewhat unusual conditions which were specified as follows:—

When taking the undermentioned amounts of power the electric output of a generator shall be as follows:—

Horse-power (metric)	120	300	500	750
Kilowatts output	77·8	206	347	510
Volts at terminals	550	550	550	550
Revolutions per minute	100	100	100	96

[This allows for a 4 per cent. drop in the engine-speed at top load.]

The generators must be able to develop an output of 347 kilowatts for a continuous run of 18 hours without the temperature rise in any part exceeding 35° C. They must be able to endure an exceptional overload up to 520 kilowatts for two hours, and a temporary one up to 675 kilowatts. Mechanically they must be able to stand a casual doubling of the speed, and electrically must stand a test of 2000 volts between winding and frame. At a constant speed and with a fixed position of the handle of the exciter rheostat, the voltage shall rise from 550 to 588 volts, or shall fall to 512



ea
wi
th
I
de
do
br
Lo
fou
dia
an
ab

50
ma

tra
wh

ele

top

kilo
per
able
for
Me
of
bet
a fi
volt

volts when the load of the machine being at first 250 horse-power, shall be respectively reduced to zero or raised to

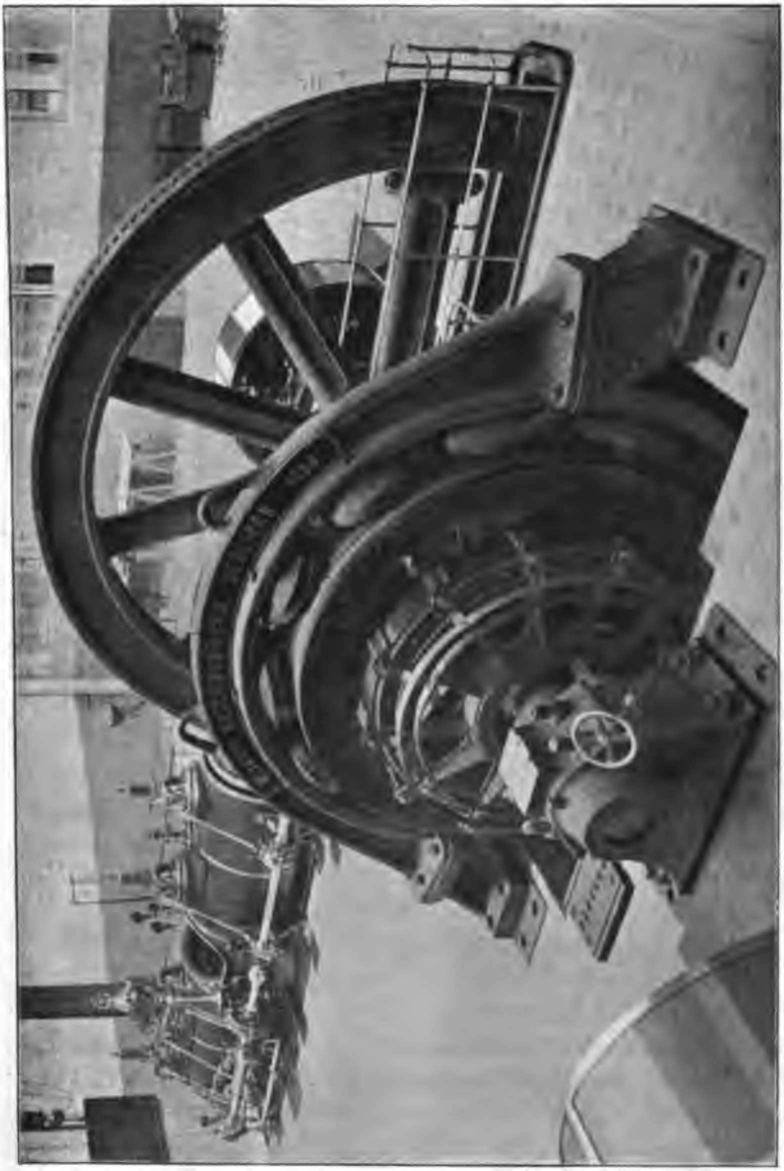


Fig. 419.—Oerlikon Co.'s 12-pole Generator, MP 12—500—100—550v—900A, at Basel.

500 horse-power. If the speed of the steam engine is raised or lowered 3 per cent. the resulting change of voltage shall not be greater than 12 per cent. Each generator is a pure shunt machine.

This generator, which represents the normal type "G 120" of the Oerlikon Company, has the following principal dimensions:—The diameter of the armature is 98½ inches, the length between core-heads 14¼ inches, and there is a single ventilating duct about 0·8 inch wide. There are 1326 conductors each 0·472 by 0·138 inch, two such being placed in each of 663 slots; each slot being 0·236 inch wide and 1·18 inch in depth. The gap-space is 10 millimetres or 0·3937 inch. The core-segments are mounted on a cast-iron spider. The winding is a series-parallel wave with six circuits from brush to brush, the winding-step being $y_1 = y_2 = 111$. This reduces the number of conductors to half that which would have been necessitated had a parallel winding (12-pole, 12-circuit) been adopted. The commutator is composed of 663 segments of hard-drawn copper built up upon a cast-iron ring, and the commutator risers connecting the segments with the winding are of iron. The commutator is about 71 inches in diameter and has an active length of 6 inches. There are 12 ranges of carbon brushes with 6 brushes in each range, mounted on a bronze support. The yoke of cast-steel, bored on its inner face, is cast in two parts. The 12 pole-cores are cylindrical, of cast-steel, with a diameter of 13·825 inches. Their basal faces are turned off to fit the bored face of the yoke, and each is secured with two screws. The shunt-coils on the bobbins consist each of 950 turns of a wire 0·141 inch in thickness. The steel yoke is stiffened by a single rib of girder section. It will be noted that the pole-cores are in this machine relatively short. The whole magnet-frame stands on two feet at the sides upon two cast-iron foot-steps which are secured into the concrete foundation. The front bearing is screwed down to a separate foot-step. The design of these bearings is separately shown in Fig. 345. They are provided with oil-rings for automatic lubrication. The weight of the magnet-frame and pole-cores is about 9½ tons, with about $1\frac{1}{2}$ tons of copper in the twelve magnet-bobbins. The armature weighs about 11 tons; there being about 4·7 tons of iron stampings, 1320 lb. of copper conductors and 880 lb. of commutator segments.

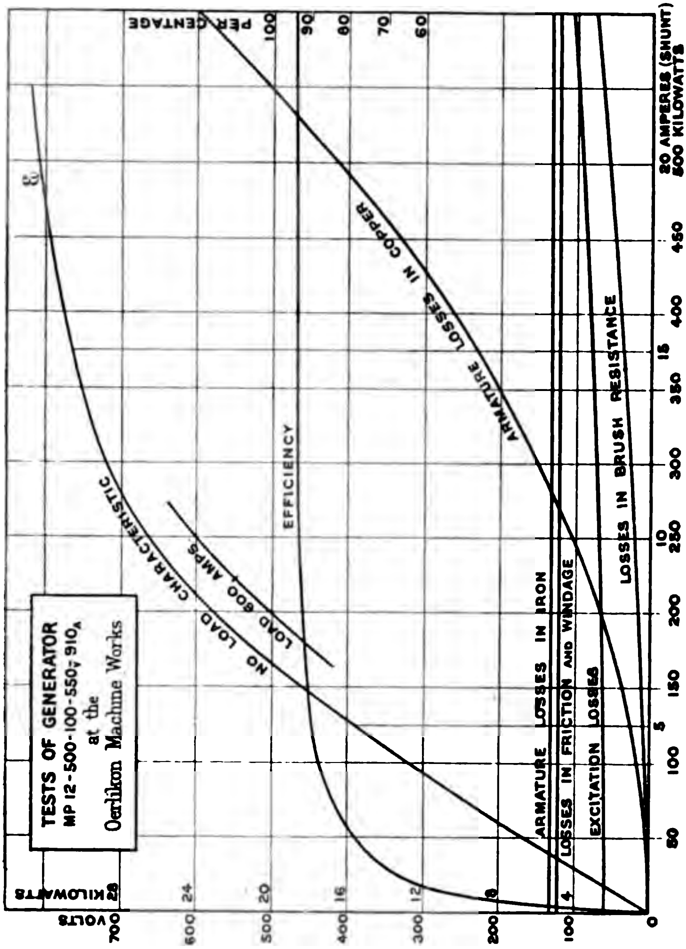


FIG. 420.—TESTS OF OERLIKON 12-POLE GENERATOR.

Tests made on the completed machines show the following results. Shunt winding resistance 38 ohms, armature resistance (brush to brush) 0·02 ohm. Efficiency at all loads from 350 to 500 kilowatts about 94 per cent. The temperature-

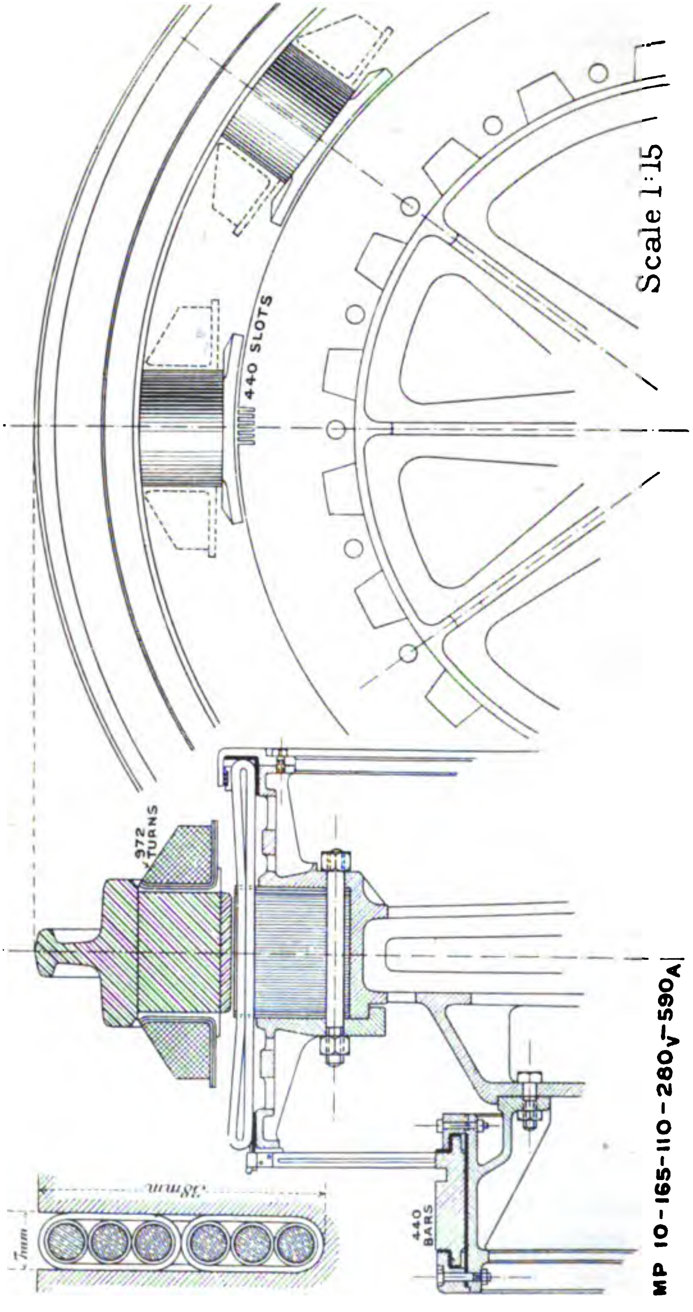


FIG. 421.—OERLIKON CO.'S 10-POLE LIGHTING GENERATOR.

rise after 12 hours at full-load was about 25° C. At all loads and even with sudden changes of 300 to 1000 amperes, and with fixed position of brushes, the machines were reported to show no sparks at the commutator. Fig. 420 gives a graph of these tests and shows the no-load characteristic of the machine.

Another recent Oerlikon machine is shown in Fig. 421, which is a lighting generator supplied to Bordeaux. This is M P 10—165—110—280 volts—590 amperes. It has 440 slots with six conductors in each slot, the coils being former-wound with three conductors in the upper and three in the lower half of the coil. The commutator has 440 segments. The coils are joined up as a lap-winding, the end of one to the beginning of the next, and each junction is united by an inverted butterfly evolute riser to two segments of the commutator situated 88 segments apart (corresponding to the double pole-pitch), thus tending to equalize the currents to be collected at the brushes. The dimensions of the slot are 1·497 by 0·295 inch. The magnets are shunt-wound, with all ten coils in series; each coil having 972 turns of a wire 0·131 inch in diameter covered to a diameter of 0·150 inch. The no-load flux is 5·8 megalines. The efficiency is 90 per cent. from half-load to full-load. Steinmetz coefficient 2·24. Ampere-conductors per inch, 660.

Messrs. Brown, Boveri & Co., of Baden (Switzerland) have constructed many types of machines for continuous currents. A leading feature of most is the barrel-winding in two superposed cylindrical layers, patented in November 1892 by Mr. C. E. L. Brown. Fig. 422 shows their normal type of belt-driven machine with cast-steel yoke, and steel pole-cores. All the larger sizes have laminated pole-shoes screwed on. In the case of compound machines the series and shunt-coils are separately former-wound, the series-coils being nearest the armature. The spider is of cast-iron. The binding wires are of bronze. The pole-cores are each secured by one central screw and a steady-pin.

Fig. 423 depicts an interesting machine which departs from the normal type in one respect. It is a *double-current* *machine*; being furnished not only with the ordinary commutator to yield continuous currents, but also with three slip-rings, that it may at the same time furnish a three-phase alternating current. The rocker-ring is bracketed out from the yoke, while the brushes for the slip-rings are supported from the pedestal of the bearing. The chief data of this machine, which was constructed for the lighting station at Alloa (Scotland), are as follows :—M P (cont. and 3-phase)—8—194—350—490 volts (or 300 Δ volts)—396 amperes. The armature core-body is 42·1 by 12·4 inches, with 128 slots 1·9 inch deep and 0·49 wide. In each slot are 12 conductors, four-deep, each having a section 0·325 inch by 0·13 inch. The over-all length of the armature windings is about 25 inches. The gap is 0·355 inch. The magnet-cores are 7·9 inches in radial length, and 10·2 inches in diameter. The outside diameter of the yoke is 71·9 inches. The commutator is 32·4 inches in diameter, and the segments 6·9 inches gross length, there being 384 segments. The magnets

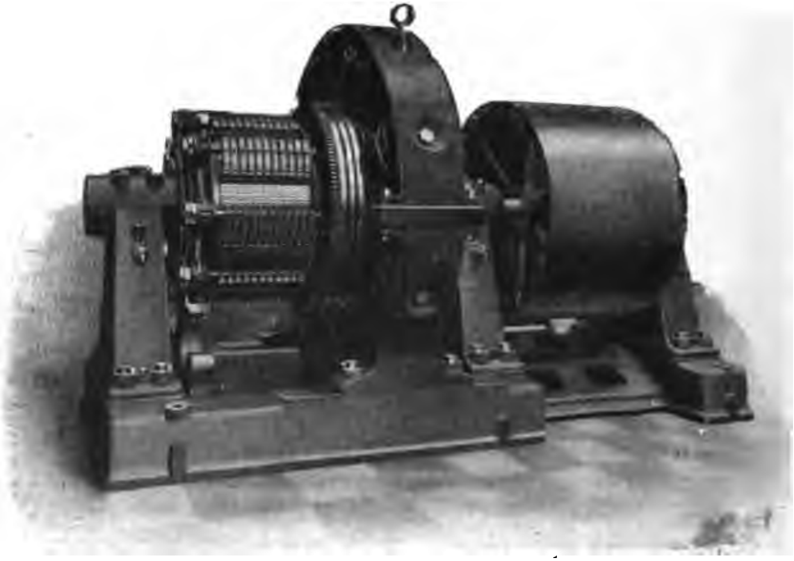


FIG. 422.—BROWN, BOVERI & CO.'S NORMAL TYPE (1901).

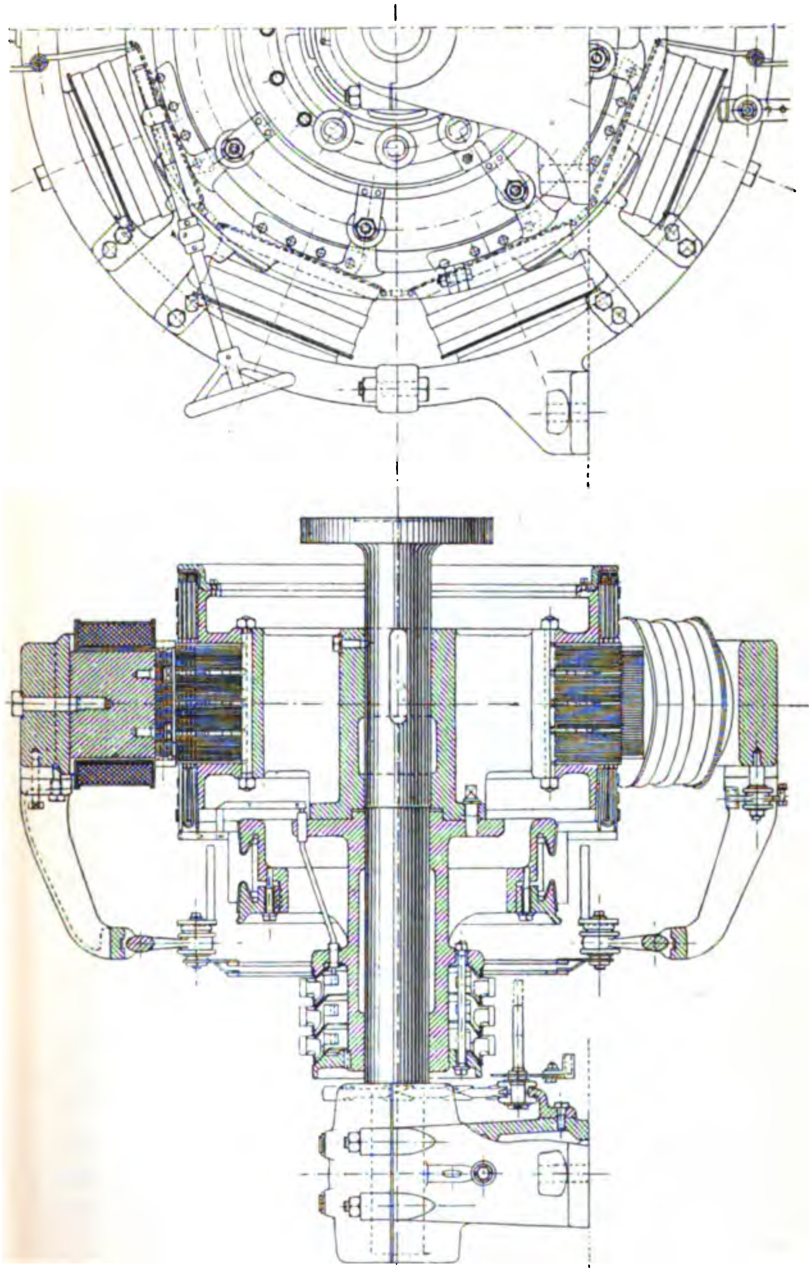


FIG. 423.—DOUBLE-CURRENT GENERATOR OF BROWN, BOVERI & CO.

are shunt-wound with 1820 turns on each bobbin, the wire being 0·083 inch in diameter. The space-factor in the slots is 0·315; that of the magnet-coils 0·568. The current density in the armature is 1920; in the shunt-coil 962; at the brush contacts 40 amperes per square inch. The flux-density in the gap is 42,000, and in the teeth 116,000 at no-load. The no-load excitation is 6600 ampere-turns per pole, of which the gap and teeth require about 5360. The cross-magnetizing ampere-turns are about 6600, and the demagnetizing 3000. Ampere-conductors per inch of periphery 520.

Plate IX. gives a drawing of a 4-pole barrel-wound drum-armature, and shows the essential constructional features of this type.

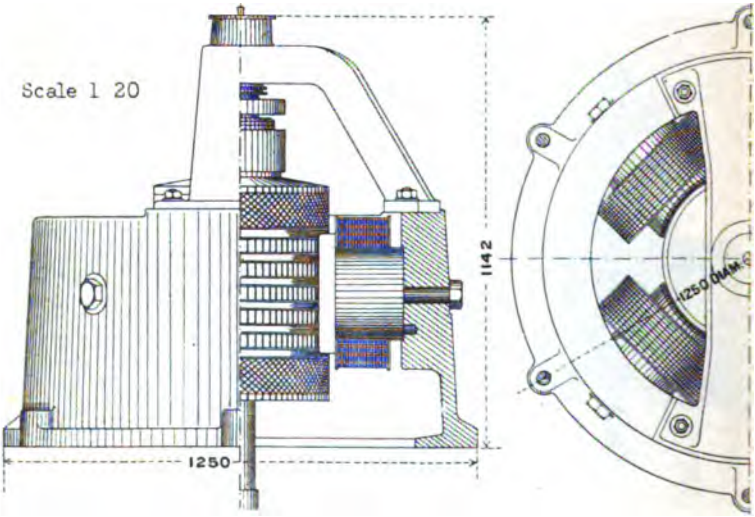


FIG. 424.—4-POLE VERTICAL EXCITER DYNAMO FOR TURBINE-DRIVING.

Fig. 424 shows the type of dynamo suitable for being driven by a vertical-shaft turbine. This example is taken from a machine used as an exciter in the turbine-house of the town of Aarau. This is a 16-kw. machine, running at 300 revs. per min.; giving 200 amperes at 80 volts, and is used for exciting the large "umbrella" alternators in the power station. Its height is about 45 inches from the bed.

Of late Messrs. Brown, Boveri & Co. have designed special machines to be coupled direct to Parsons' steam turbines. The very high speeds have necessitated sundry modifications in design. The armatures are relatively smaller in diameter and of greater length, and the field-magnets are provided with a special mode of cross-compounding. One of these machines, of 100 kilowatts, is described on p. 759.

Messrs. Scott and Mountain make a standard line of generators from a 12-pole 78-inch by 13-inch generator of 280 kilowatts and 90 revolutions to a 4-pole 42-kilowatt machine at 680 revolutions, the larger sizes being, of course, for direct coupling, and the smaller ones rope-driven. These machines throughout are characterised by solid mechanical construction, the large relative size of bearings, in all sizes, being especially noticeable. The mechanical construction of the armature is simple, the armature laminations being held upon a spider by stout bolts. In the larger sizes, the commutator is bracketed out from the arms of the spider, and in the smaller sizes the commutator is built up on an extension of the armature hub, the whole being held against a shoulder on the shaft by a threaded ring kept home by a grub-screw. Slotted drum armatures and barrel-windings are used throughout; the pole-cores are of cast-steel, while both cast-iron and cast-steel yokes are used, the former in the larger sizes. The armature conductors, instead of being bent round and in one continuous piece at the back of the armature, are clamped together with a copper clip and the whole then soldered, this construction being considered to give special advantages in repairing. In the machine having four conductors per slot (see Plate V.) the conductors are first taped, then a pair of them are wrapped with manila paper and placed in the slot, which again is lined with varnished millboard. In this particular example the total thickness of insulation between conductor and core is ·075 inch. In connecting to the commutator, the commutator-risers are let into the commutator-bars, and then both soldered and riveted, thus making an excellent joint both mechanically and electrically. The binding-wires are insulated from the armature-core with

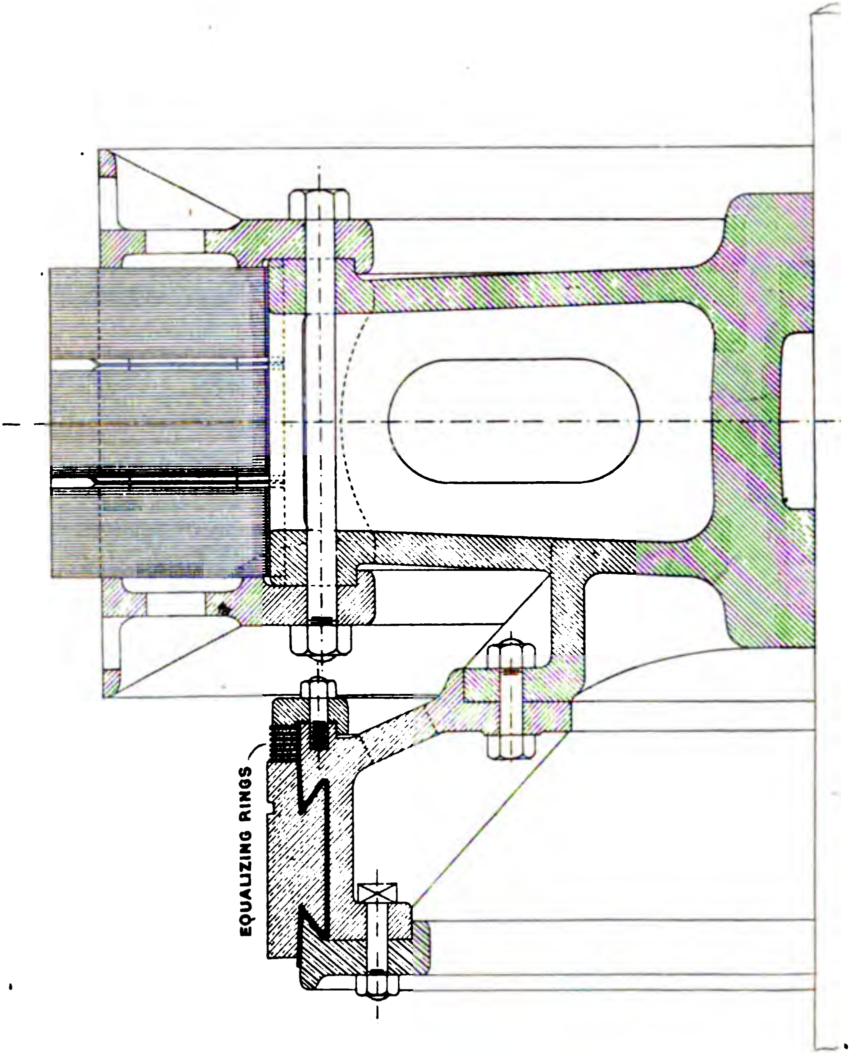
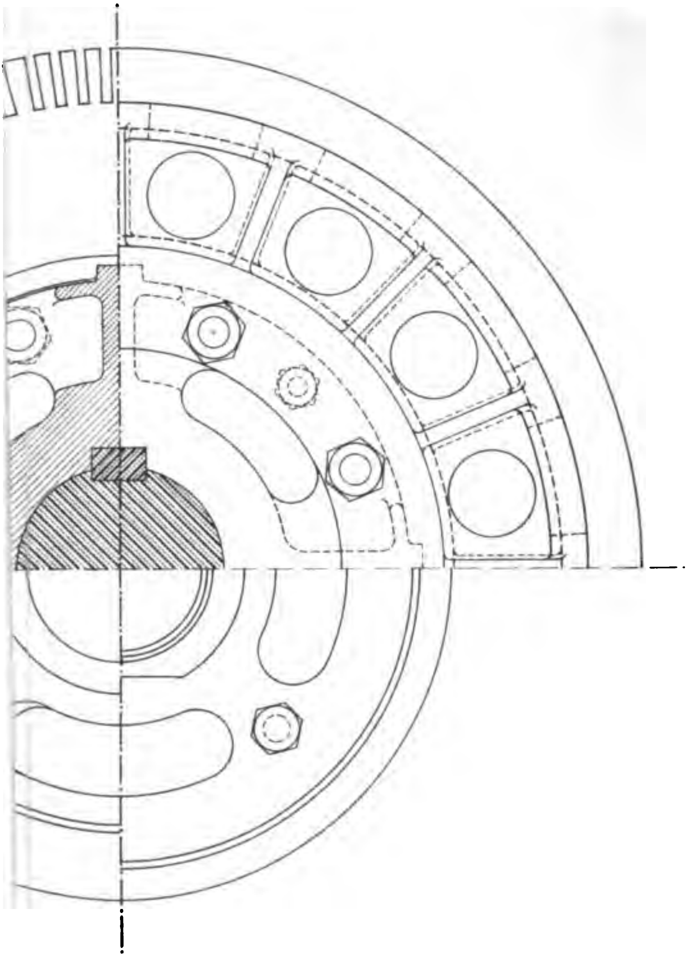


FIG. 425.—SCOTT AND MOUNTAIN MP 12—280—90, SHOWING EQUALIZING RINGS.

one turn of varnished millboard and mica slips. The commutator construction possesses no unusual features. Equalizing rings are used in the larger sizes, built up against the



ENERATOR.

TS 600 AMPS.

in, Newcastle on Tyne.

Thos Kell & Son Lith

back of the commutator, and held by a cast-steel clamping-ring. In a particular case of the 12-pole 28-kilowatt generator (see Fig. 425), equalizing rings, six in number, are used, these rings being built up with the commutator, behind the commutator-risers, and insulated as shown. The six copper rings are 1 inch in depth and $\frac{1}{8}$ inch thick, the insulation between the rings being 0·09 inch in thickness and the insulation at the ends $\frac{1}{8}$ inch thick.

This firm aims at high flux-densities throughout, running the flux up to B = 140,000 or more at roots of teeth and over 100,000 in the magnet-cores; and using also a fairly high gap-density. The field-bobbin construction in these machines is a detail worthy of note. The bobbins are made with sheet-iron cores and thick teak flanges, which have a good appearance, but which would seem to take up a good deal of valuable space.

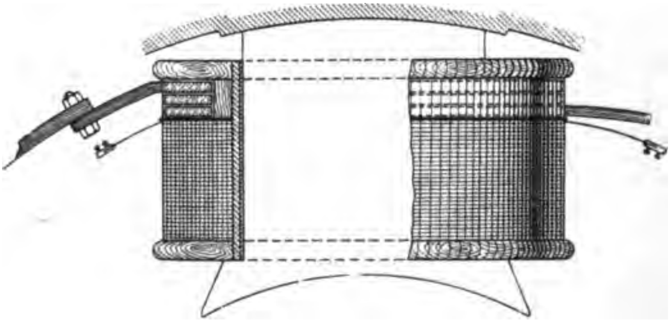
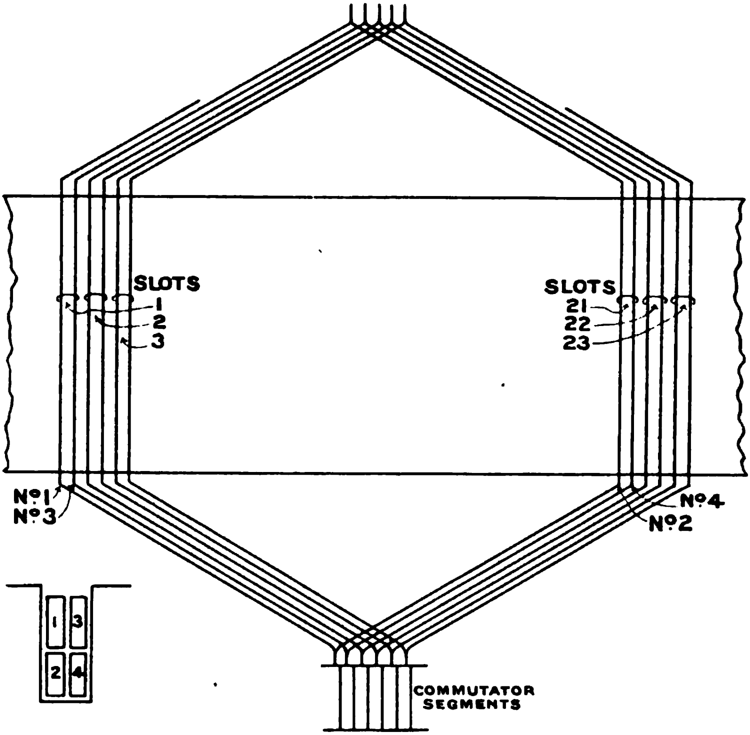


FIG. 426.—FIELD-MAGNET OF 6-POLE GENERATOR OF SCOTT AND MOUNTAIN.

Fig. 426 shows a detail drawing of bobbin construction for the Scott and Mountain 6-pole generator depicted in Plate V. For insulation over the sheet-iron spools two layers of varnished canvas and one complete layer of press-spahn 0·06 inch thick are used. According to the makers, the use of these sheet-iron cores, thus enabling the winding readily to communicate its heat to the frame of the machine, permits the use of very high current-densities in the field-bobbins. They are thus enabled to use current-densities of over 1000 amperes per square inch in the field winding, and by thus shortening the necessary winding space, the over-all dimensions of the machine may be reduced, and consequently the cost.



FRONT. *Join 1 (upper) in N° 1 slot to 2 (lower) in N° 21 slot*
BACK. *„ 2 (lower) „ „ 21 „ „ 3 (upper) „ „ 1 „*
FRONT. *„ 3 (upper) „ „ 1 „ „ 4 (lower) „ „ 21 „*
BACK. *„ 4 (lower) „ „ 21 „ „ 1 (upper) „ „ 2 „*
and so forth.

FIG. 427.—WINDING DIAGRAM OF SCOTT AND MOUNTAIN 6-POLE GENERATOR.

Fig. 427 shows the winding scheme of the 6-pole machine described, the design of which is analysed at the beginning of Chapter XIX. p. 582.

The compounding conductor is of rectangular strip, wound edgewise, as shown in the detail drawing. These coils are wound bare, then opened out slightly and taped. Connexion of one series coil to another is made by flexible copper couplings bolted on. Carbon brushes are used throughout without exception in machines by this firm, the current density in the carbon being about 30 amperes per square inch in the larger machines and about 15 amperes in the smallest size. An extract from a very usual form of guarantee for these machines, supplied by the makers, is as follows:—There shall be no sparking due to variation of load within the limits of no-load and 25 per cent. overload, the machine

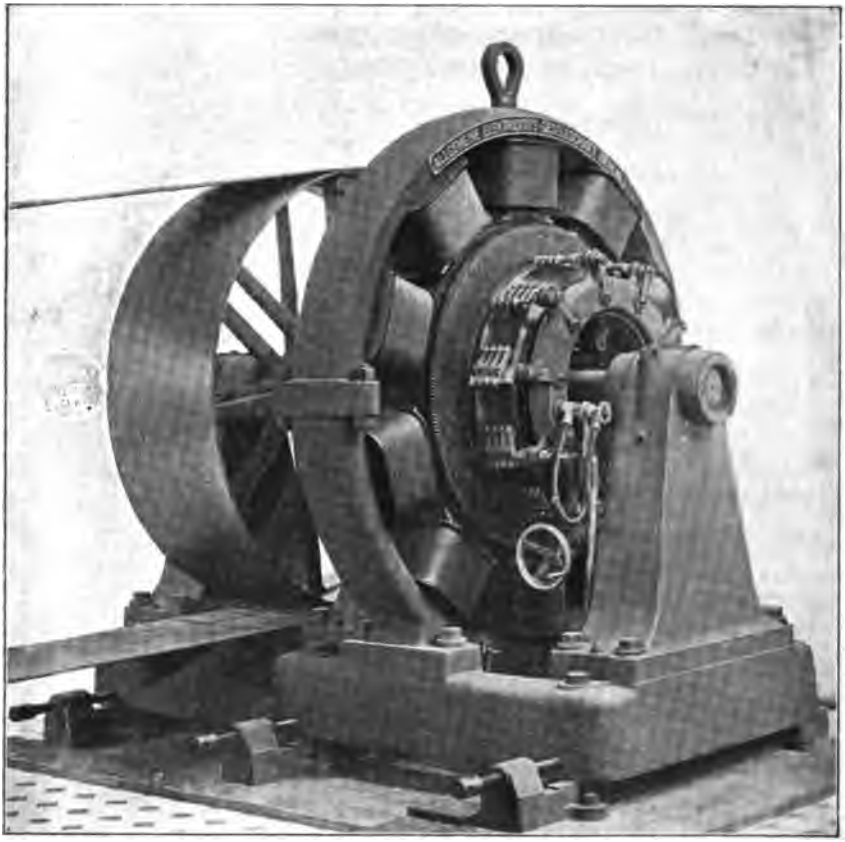


FIG. 428.—DYNAMO OF THE ALLGEMEINE CO., M P 10—142—270.

to run continuously with practically no sparking or burning of the brushes, and without blackening the commutator.

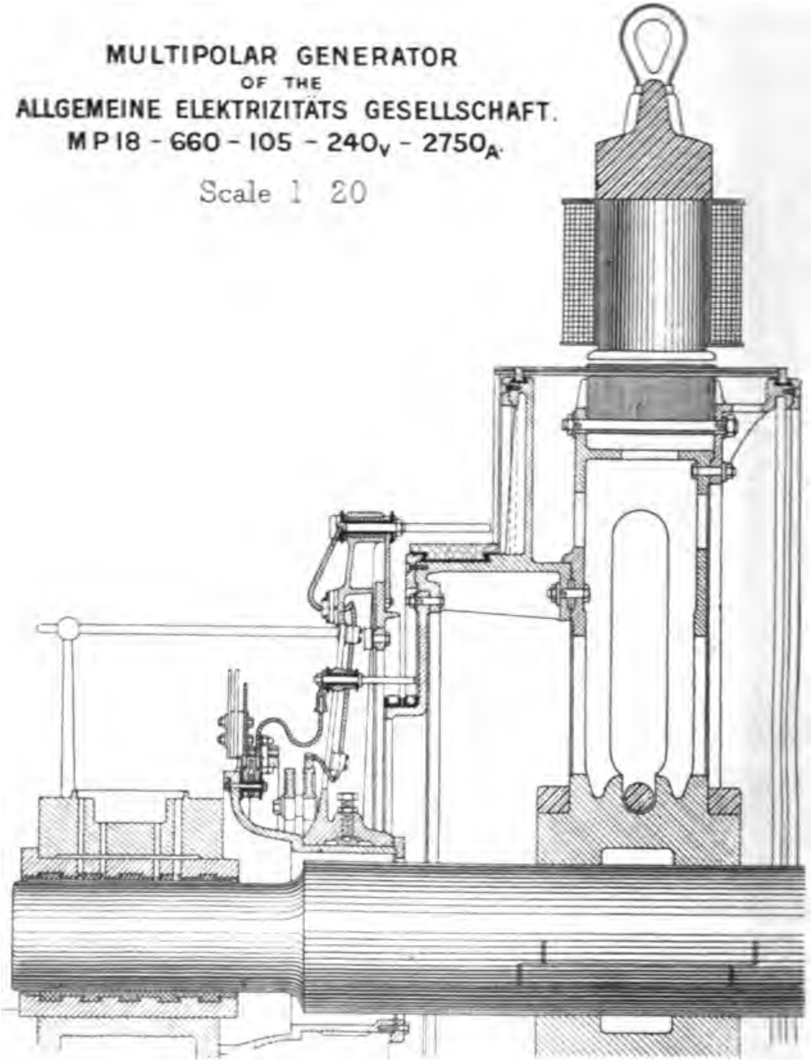

MULTIPOLAR GENERATOR
OF THE
ALLGEMEINE ELEKTRIZITÄTS GESELLSCHAFT.
MP 18 - 660 - 105 - 240V - 2750A.
Scale 1 : 20

FIG. 429.

The machine to stand a momentary overload of 50 per cent. without sparking with fixed brushes, and the armature to stand an alternating potential of 2000 volts without damage.

Fig. 428 illustrates a belt-driven 10-pole machine of the Allgemeine Elektrizitäts Gesellschaft, designed for 257 amperes at 550 volts. These machines, with cast-steel yokes and pole-cores, are lighter than the machines of equal output and speed with fewer poles; a higher peripheral speed being attained by designing the armature of large diameter relatively to its length. The armature of this machine is depicted separately in Fig. 336, p. 461.

The generator, shown in Fig. 429. by the Allgemeine Elektricitäts Gesellschaft, has 18 poles, with an output of 660 kw. at 240 volts running at 105 revolutions per minute; the current is thus 2750 amperes.

There are 1152 turns of shunt winding per pole (16 layers 72 turns per layer) the wire having a diameter base of 4·5 mm., insulated with double cotton covering to 5·1 mm.; the total length of wire per bobbin is about 1452 metres, the resistance for a single bobbin being 1·6 ohm, and the total weight of the wire on the whole field (18 bobbins) being about 3730 kilo. The field is excited in two parallels of 9 bobbins for each parallel.

The armature has 720 slots with 2 conductors per slot, the dimensions of the conductors bare being 4·2 × 7·2 mm., the length of one conductor with its end connections being 1·19 metre, and the total length through the whole winding is about 1700 metres. The resistance of the armature at 15° C. is approximately 0·0031 ohm.

A wave-winding is employed, the total number of conductors being 1440, the pitch being 79 conductors; the winding thus goes round the armature 18 times, and there are 18 parallel circuits through the armature.

The firm of Kolben & Co., of Prag, has made itself known for the excellent types which Mr. Kolben has produced during recent years.

Fig. 430 depicts a small 4-pole machine of this firm, of

3 kilowatts output. Though it has four poles, two of them only are wound, the other two being consequent poles at the sides of the magnet-frame. Running at 1100 revolutions per minute, it generates 25 amperes at a pressure of 123 volts at the terminals. The magnet-frame and cores are of cast-steel; the bearing supports of cast-iron. The external diameter of the core-disks is 9·11 inches; the internal 4 inches. The length between core-heads is about 4½ inches. There are 69 slots, each 0·788 inch deep and 0·167 inch wide. In each slot are 6 conductors, making 414 conductors in all, their diameter being 0·087 inch bare, covered to 0·110 inch. The gap-space is 0·118 inch. The commutator, of 69 segments, is 4 inches in diameter, 2 inches long, and the mica insulation is 0·024 inch thick. There are two sets of carbon brushes with two brushes on each set, of a size allowing 1 square inch for 30 amperes. On each pole-core are wound a shunt coil of 2300 turns of a wire 0·040 inch diameter covered to 0·055 diameter, as shunt, and 28 turns of a series winding

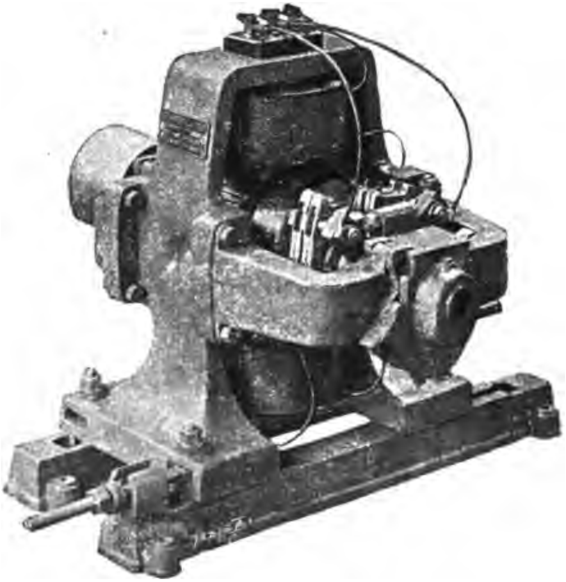


FIG. 430.—KOLBEN'S 4-POLE 3-KW. DYNAMO.

en
the
per
at
e.;
of
The
to
ch

eir
he
s.
on
es
h
il
to
s

Cons

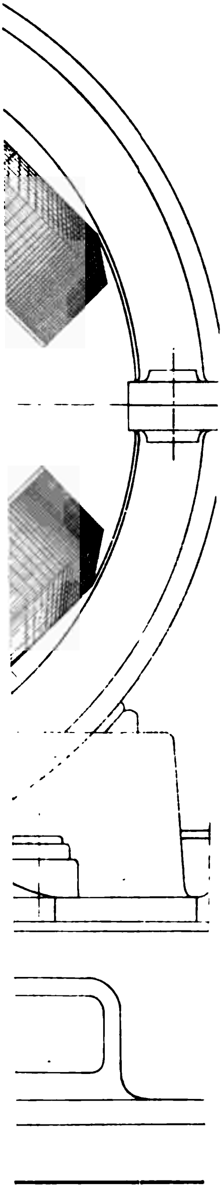
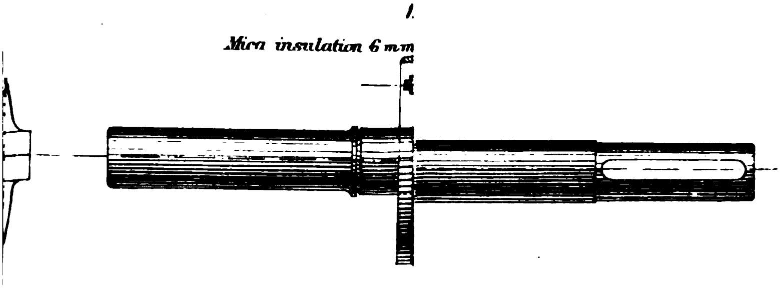
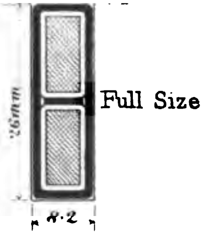


Plate VI.

tructed by Kolben an
of Prag.

Scale 1:10





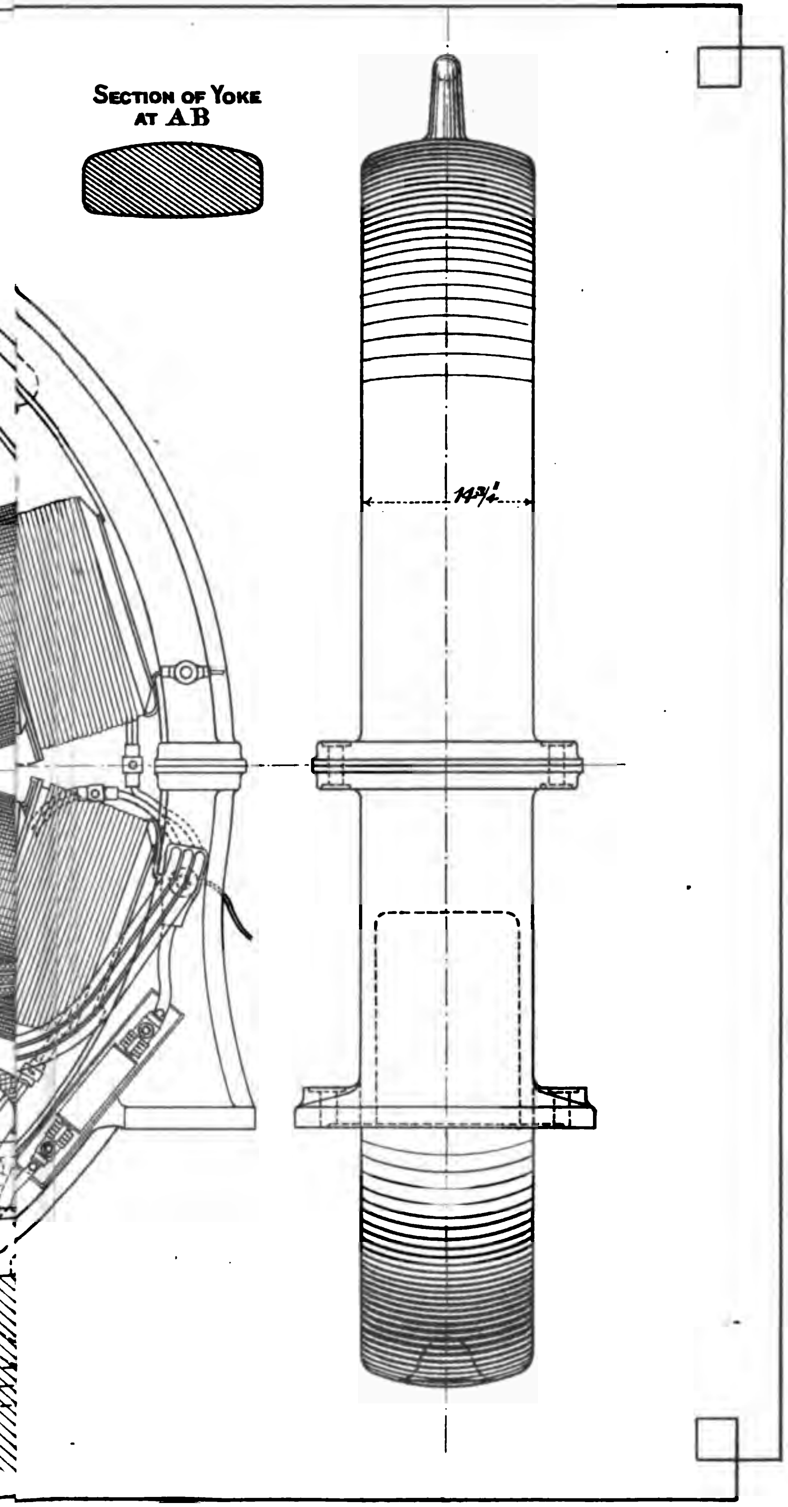
CONTINUOUS

MP—4

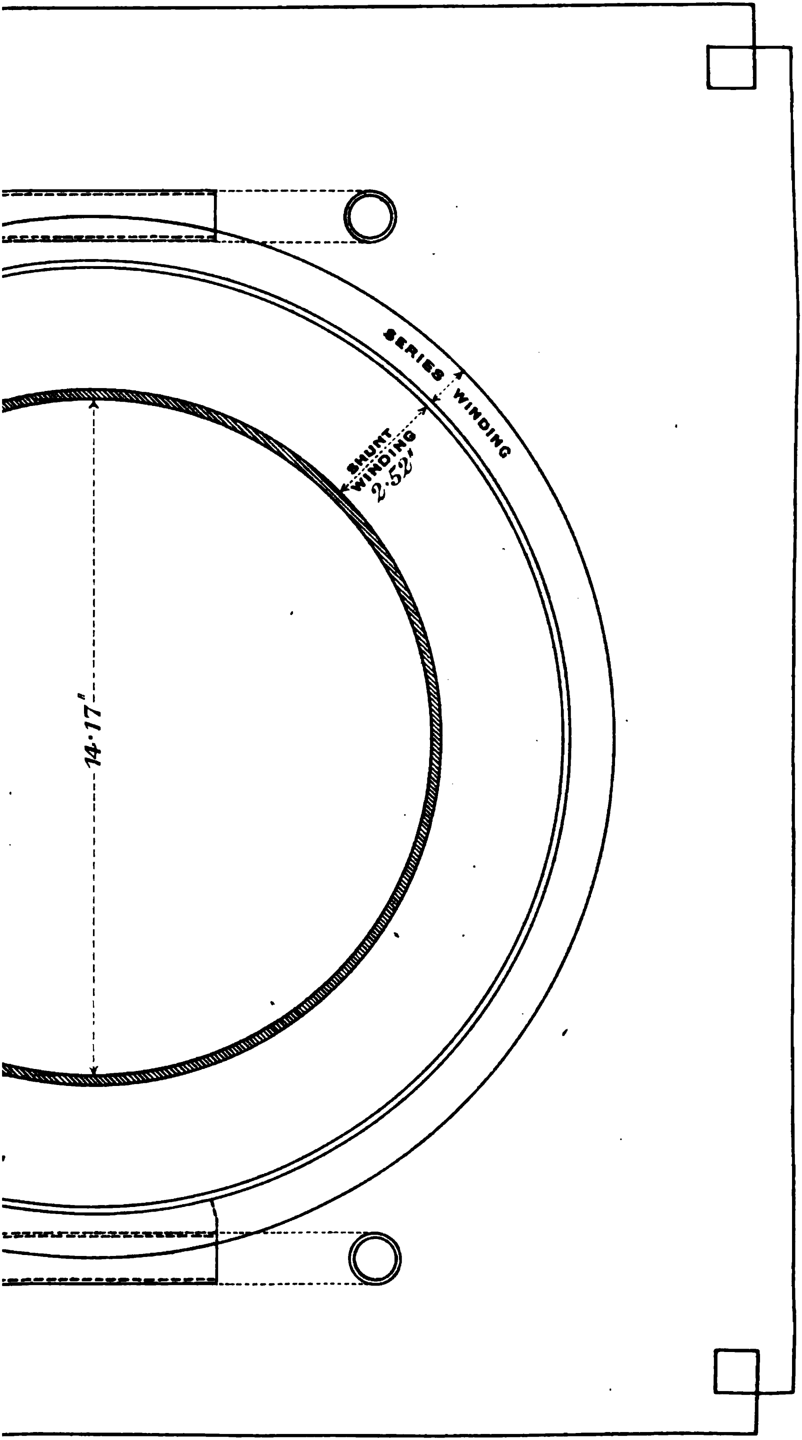
forming porti
being coupled to a

E.&F.N. Spon Ltd London.
Thos Kell & Son, Lith.

Plate XVI



Thos Kell & Son, Lith.



Thoˢ Kell & Son, Lith

0·173 inch in diameter covered to 0·193 inch. The efficiency at full-load is 85 per cent.

In Plate VI. is shown a Kolben M P 4—70—750 generator forming part of a motor generator set, being coupled direct to a synchronous single-phase motor. It gives 270 amperes at 260 volts. The yoke and pole-cores are in one casting of steel, and cast-steel pole-shoes are attached by screws to the pole-cores.

The field-spools have each 2400 turns of wire 0·07 inch in diameter, all being of course in series; the length of the winding space is, excluding insulation, 7 inches, and the depth of winding space 2·55 inches. The armature is 23·2 inches in diameter, and the length between core-heads 13·9 inches; there are no ventilating ducts. A wave-wound barrel-winding is used, there being two circuits with 226 conductors, two conductors per slot, the number of slots being therefore 113. The conductors are rectangular, having a cross-sectional area of 0·085 square inch, and the slots are 0·32 inch wide and 1·06 inches in depth. The mechanical design throughout shows the utmost simplicity, the design of the armature spider being especially neat. The commutator has 113 segments and is 13¾ inches in diameter.

Plates XVI., XVII. and XVIII. show a Kolben traction generator, M P 10—250—125—550 volts—454 amperes. Its general aspect is shown in Fig. 431.

The ten pole-cores are cast in one piece with the yoke, the whole being of cast-steel, with cast-steel pole-pieces screwed on. Plate XVIII. shows in detail the construction of the field-magnet bobbins and pole-pieces. The pole-pieces are skewed in order to ensure that the armature conductors in revolving shall come gradually into the field. This machine is compounded, each pole having 5½ turns of copper strip 5·32 inches wide and 0·059 inch in thickness wound outside the shunt-turns. The outside diameter of the yoke is 105 inches, the maximum radial thickness being 5·9 inches; the pole-cores are 13·97 inches in diameter. The field is bored to 67·25 inches, and the diameter of armature is 66·1 inches, the gap therefore being 0·575 inch long. The armature is wave-wound, the winding being a series-parallel, having four circuits in parallel, with ten sets of brushes. There are 437 slots, each 0·256 inch wide and 0·984 inch deep, and two conductors of 0·0652 square inch section, in each slot; there being thus in all 874 conductors. The space-factor that is to say, the ratio of copper section to slot section, is 0·516.

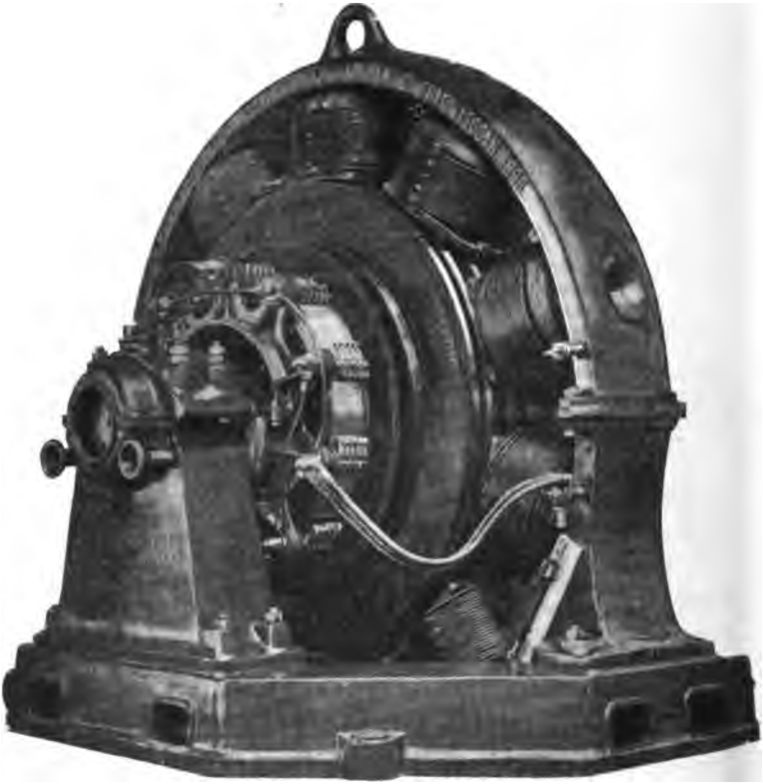


FIG. 431.—KOLBEN'S 10-POLE TRACTION GENERATOR.

The end connexions of the armature conductors are made by joining them together at separate insulated copper segments, held round the armature exactly like commutator segments, this construction being exceptionally good

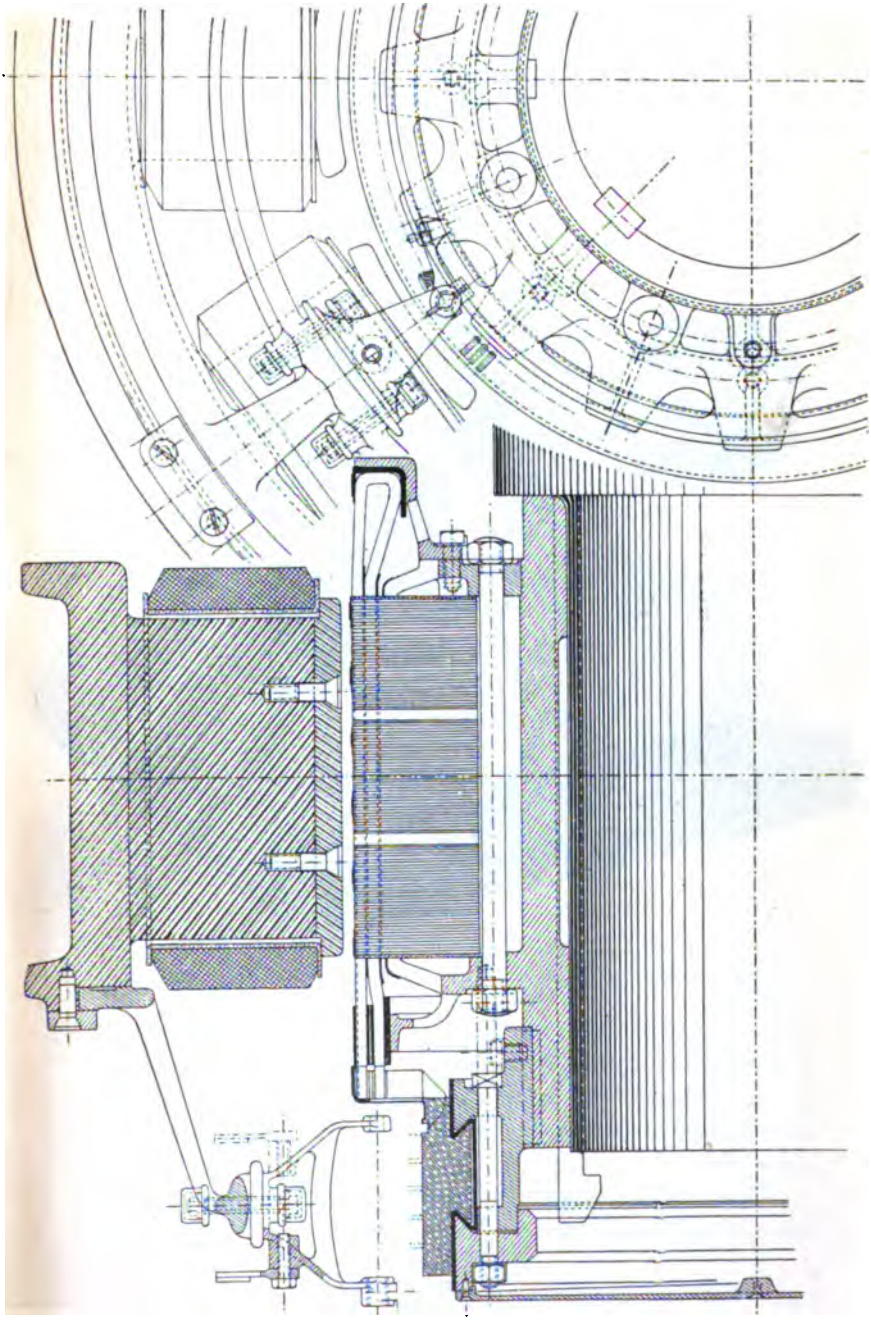


FIG. 432.—SLOW-SPEED EXCITER DYNAMO, MP X 10—38—75 (KOLBEN & CO.).

mechanically; the commutator risers are then simply sweated into cuts in these segments. The commutator has a diameter of 39·35 inches; there are 437 segments, or one segment per slot. Mica 0·036 inch thick is used for insulation between the segments. This generator is for direct coupling to engine, a flange being provided for the purpose on the end of the shaft. The armature spider is secured firmly to the shaft by means of steel rings pushed on to a shoulder on the spider while hot, the subsequent contraction effectually gripping the spider to the shaft.

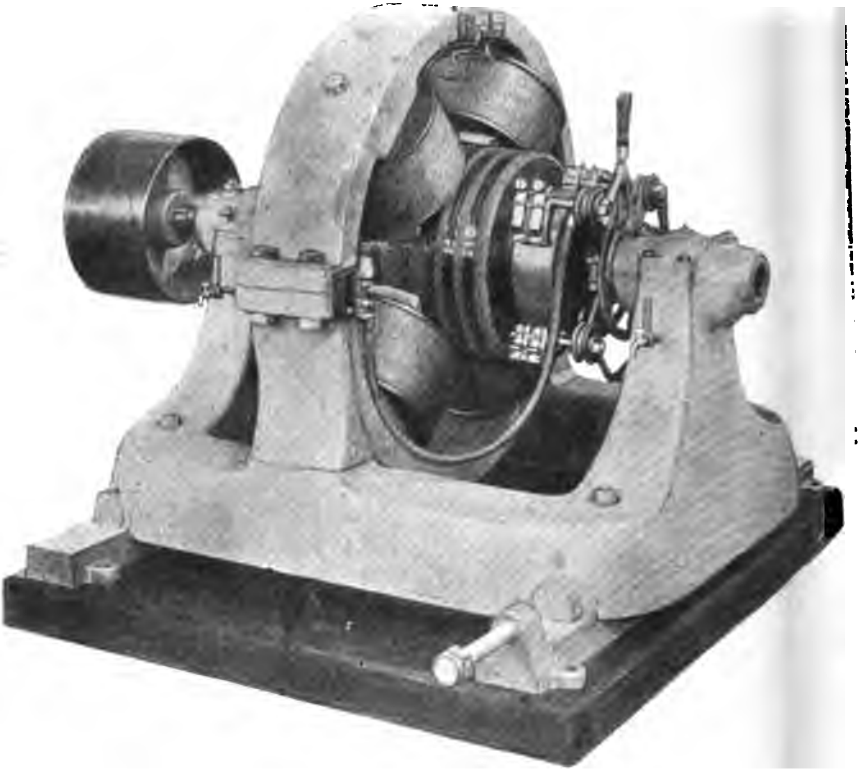
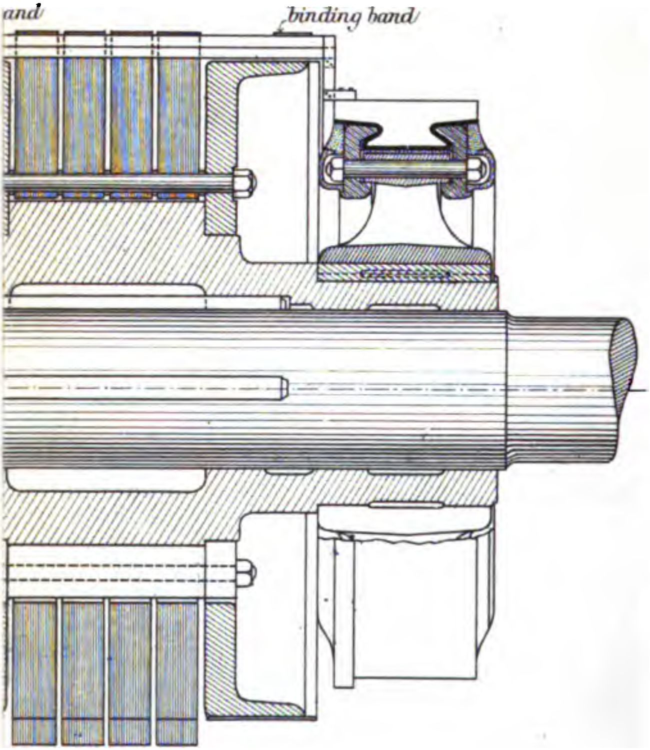


FIG. 433.—GENERAL ELECTRIC CO.'S MULTIPOLAR DYNAMO.

The winding-scheme of this machine is specially considered and described on p. 401 above.

Plate X.



TREET-TRAMWAY GENERATOR

525 VOLTS, AT 200 REVS. PER. MIN.

gned by Mr. H.F. Parshall.

Tho: Kell & Son Lith

Fig. 432 illustrates a special type of generator, namely, a very slow-speed *exciter*, destined to be mounted on the end of the shaft of a large alternator, revolving at only 75 revolutions per minute. This entails peculiar variations in the construction.

The diameter of the core-disks is 33·8 inches; the length between core-heads 15·1 inches; and as the output is only 38 kilowatts the Steinmetz coefficient reaches the abnormal value of 13·4. The commutator has a diameter only slightly less than that of the armature, the risers being necessarily very short. The machine is shunt-wound.

An 18-pole electrolytic machine of Messrs. Kolben & Co. is described in Chapter XXI.

General Electric Co.'s Dynamos.—At the Schenectady works the bipolar Edison type of dynamos has long been superseded by multipolar machines, closely following the types developed in Switzerland. Fig. 433 gives a general view of a 60 kilowatt machine of the standard type adopted for the sizes under 100 kilowatts, having 4 poles. The magnet cores and yoke are of special mild steel soft castings. The windings of the armature are sunk between teeth in the core-disks, with air-ducts at intervals. The insulation consists of alternate laminations of sheet mica and tough paper.

Fig. 434 gives a view of a 6-pole traction generator of 400 kilowatts for belt-driving at 150 revolutions per minute. The output is 800 amperes at 500 volts. These machines are so designed that the flux-density shall be 85,000 lines per square inch in the pole-cores, 70,000 in the yoke. In the armature disks the density is also 70,000 lines per square inch, increased to 135,000 in the core-teeth, this high degree of saturation being preferred as helping to prevent distortion of field. The permitted amperage in the armature conductors is only 1500 amperes per square inch. Some much larger machines have been constructed for direct-driving, as, for example, the six 1500 kilowatt machines in the Brooklyn generating station.

Mr. H. F. Parshall has kindly furnished the data for the design shown in Plates X. and XI. This represents a recent 6-pole, 150 kilowatt, machine with cylinder drum-armature, giving 300 amperes at 525 volts at 200 revolutions per minute. The core-disks are slotted with 154 teeth, between which lie the conductors in two layers. To diminish sparking a duplex winding (p. 367) is adopted, so that in

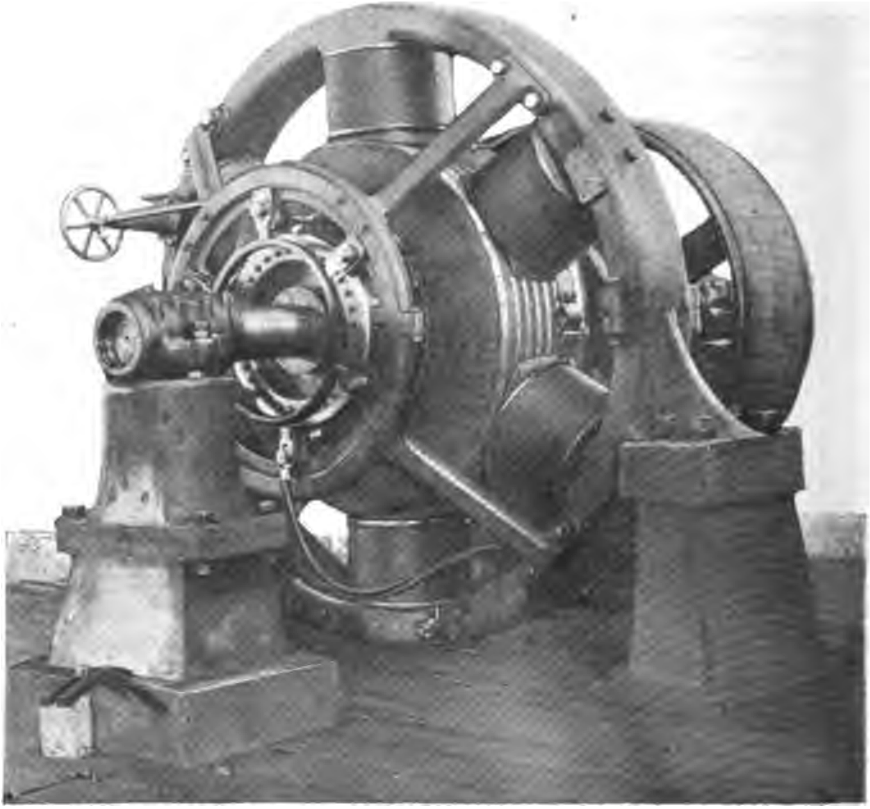


FIG. 434.—GENERAL ELECTRIC CO.'S TRACTION GENERATOR.

each slot there are 4 conductors, and in the commutator 308 parts. The mode of construction of the latter, which is peculiarly substantial, is shown in Plate XI. It will be noted that the armature core-disks, built up of overlapping segments, have internal lugs by which they are bolted together and driven upon a grooved spider. There are about 10,000 ampere-turns of excitation upon each pole, of which about 4000 are provided by the compounding coils at full-load. The shunt coil has to provide for 5815 ampere-turns which are required as follows:—4350 to drive the flux across the gap-space, 645 for the yoke, 450 for the pole-core, 300 for the teeth, and 70 for the armature body. The flux through each pole is 8,700,000 lines.

Mr. H. F. Parshall, who designed this machine for the General Electric Co., Schenectady, and has since designed many others for European firms, is the joint author with Mr. Hobart of two elaborate works on *Armature Windings* (London, 1898) and on *Electric Generators* (London, 1900). In the latter work they give very full constructional data and details of the following machines.

M P 12—1500— 75—550 volts—2500 amperes;
M P 6— 200—135—500 volts— 400 amperes;
M P 10— 300—100—125 volts—2400 amperes;
M P 6— 250—320—500 volts— 455 amperes.

Of these the first, which was built for the Chicago Exhibition of 1893, is not altogether satisfactory, and the third, a lighting machine, is distinctly an inferior design. The best is the second.

Its armature is lap-wound with 1760 conductors in two layers, in 220 slots, barrel-wound. The current-density is 1760 amperes per square inch in the armature, 6670 in the commutator risers, 800 in the shunt-coil, 770 in the series-coil, 44·5 at the brush contact. The flux-densities at full-load were as follows:—76,000 lines per square inch in armature core-body, 121,000 (apparent) in teeth, 45,000 in the gap, 96,000 in steel pole-core, 70,000 in steel yoke. The excitation percentages were allocated as follows:—

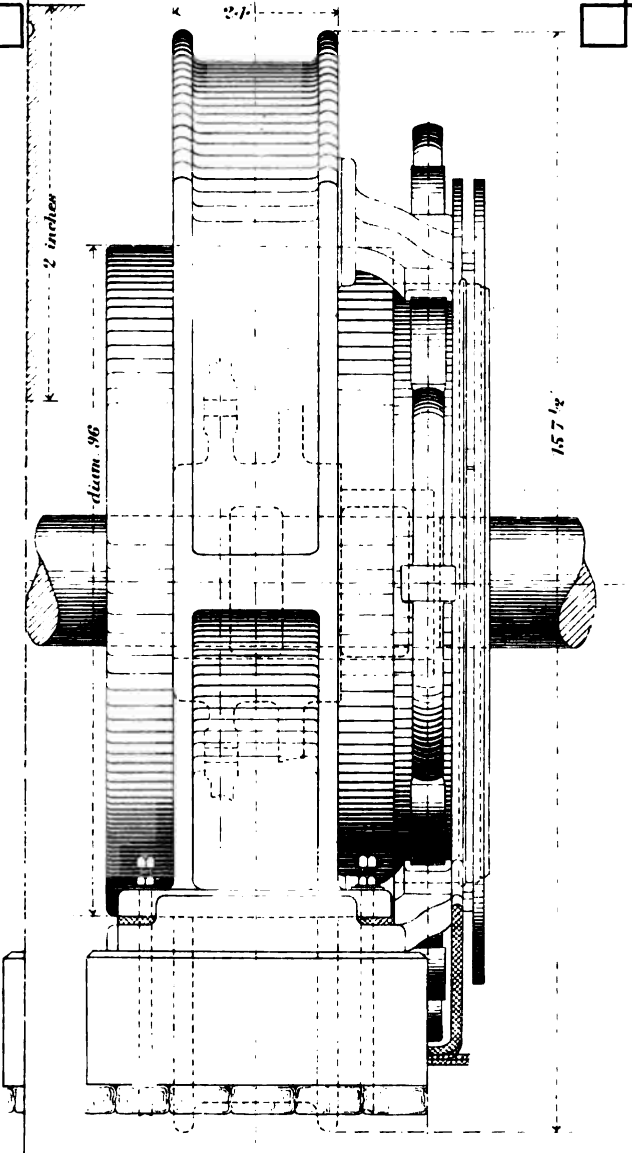
	At no-load.	At full-load.
Armature-core	4·4	5·0
Teeth	7·3	10·4
Gap	58·9	63·0
Pole-core	17·3	21·5
Yoke	12·1	14·0
Compensation for demagnetization	..	24·4
„ distortion	..	5·0
	100·0	143·3

The excitation at no-load required 7630 ampere-turns per pole; at full-load 10,990. The heat-loss in the armature was 1·70 watts per square inch of radiating surface, and the temperature rise 30° C. by thermometer or 37 by resistance measurement. The losses in percentage of the net full-load output were:—armature iron 1·38, armature copper 4·4, commutator and brushes 0·735, excitation 1·21, including series-coils and rheostat. The curves given in Figs. 383 and 384 relate to this machine.

Mr. Parshall has also published[1] very complete data of a slow-speed 550-kilowatt generator of the General Electric Company's design, which, though a rather heavy machine for its output, gave a very satisfactory performance from the point of view of cool and sparkless running. Fig. 435 shows the armature in section. Let us treat this machine as though we had to design it, adopting the order of procedure of p. 554. We are to produce a multipolar generator working at a terminal pressure of 500 volts (at no-load), and of 550 volts at the full-load of 1000 amperes, the engine speed being 90 revolutions per minute. Obviously it is to be over-compounded. The prescribed efficiency is 94 per cent. at full-load. As the full-load is 1000 amperes, if we would not attempt to collect more than 200 amperes at any one row of brushes, we must have at least 10 poles and 10 rows of brushes (5 positive and 5 negative). With a 10-pole machine with steel poles, one would expect the armature diameter to be at least five times the length of the core-body. Then applying formula No. [III], p. 542, let us assume $\mathsf{B}_g = 42{,}000$; $q_1 = 600$; $\psi = 0{\cdot}75$; from which $\kappa = 31{,}800$. Therefore $d^2 l = 31{,}700 \times 550 \div 90 = 19{,}300$; and, if $d = 5\,l$, we get $d^3 = 965{,}000$, whence $d = 98{\cdot}5$, which would give $l = 19{\cdot}7$. The dimensions actually used are $d = 96$ and $l = 20{\cdot}5$; so that the Steinmetz coefficient comes to 3·56. The peripheral speed is 2263 feet per minute, and the periphery 302 inches. This gives 30·2 inches for the pole-pitch at the armature

---

[1] *Street Railway Journal*, xvi. Oct. 1900; and *Electrician*, xlvi. 670, Nov. 23, 1900.



OLAR TRACTION GENERATOR

OWATTS 90 REVS: PER MIN: 550 VOLTS 1000 AMPERES

Constructed by the
tric Company of Schenectady, N.Y.,
esigned by H. F. Parshall

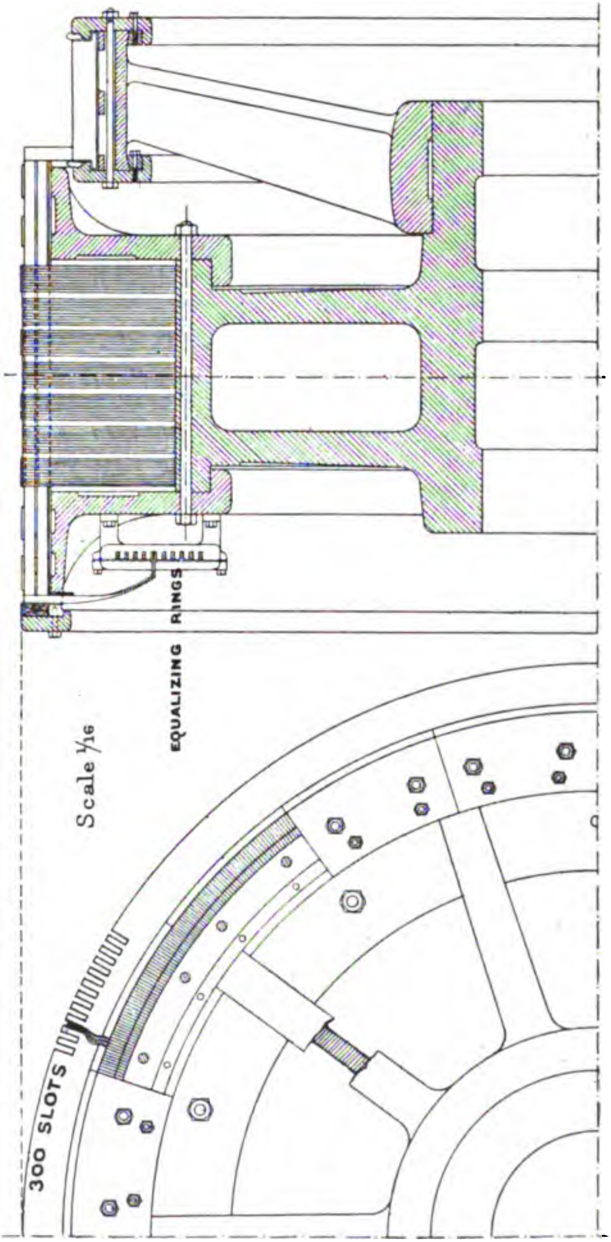


Fig. 435.—Parshall's M P—10—550—90 Traction Generator.

face. Taking the pole-arc at about 75 per cent. of the pole-pitch, or 22 inches, the area of pole-face (which is not quite rectangular, being bevelled at the outer corners to a polygonal form) will be about 22 × 20 = 440 square inches. If we take 42,000 lines per square inch (at no-load) as a suitable pole-face density, that would make the flux from one pole to be N = 18,480,000, or 18·48 megalines. Now using the formula of (VII*b*), p. 547, since *n* (the revolutions per second) = 1·5 and E, the no-load voltage, is 500, we get for the trial value of Z the number of armature conductors:—

$$500 \times 10^8 \div (1 \cdot 5 \times 18{,}480{,}000) = 1803.$$

The actual number in the machine is 1800 grouped in 300 slots, 6 conductors in each slot. Testing this by the rule that it is inadvisable to have more than 600 ampere-conductors per inch of periphery, we find 1800 conductors each carrying 100 amperes (since there are 10 paths for 1000 amperes) occupying 302 inches periphery, making 595 amperes per inch periphery, which is satisfactory. Further, as $n = 1\frac{1}{2}$, and there are 5 pairs of poles, the frequency of magnetization will be only $7\frac{1}{2}$ cycles per second. There will be, of course, 900 segments in the commutator, and as these ought to be about 0·3 inch wide, the total periphery of the commutator ought to be about 270; it is in fact 272, the diameter being 86 inches, and the length of the segment about 9 inches. As the armature periphery is 302 inches, and there are 300 slots, the tooth-pitch will be 1·006 inch. The slot should be about half this; it is in fact 0·525 inch wide. As 6 conductors each carrying 100 amperes pass through the slot, and as the current-density in the copper will be about 1500 amperes per square inch, each conductor will need to be about 0·065 square

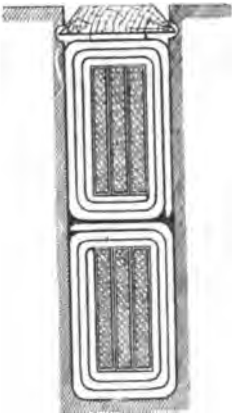


FIG. 436—SLOT OF PARSHALL'S 550-KILOWATT MACHINE.

inch in section, and the total section of copper in any one slot will be about 0·39 square inch. If the space-factor be assumed at about 0·4, this will show that the gross section of the slot must be nearly 1 square inch. As it is 0·525 inch wide it must therefore be nearly 2 inches deep. In fact, the slots are made exactly 2 inches deep, allowing for a wedge at the top. The copper conductor is 0·0641 square inch in section. The slots being 0·525 inch wide, the gap must not be much less. It was actually 0·375 inch. As this is to be an over-compounded machine there must be allowed a long pole-core, say, as a trial value, not less than 40 times the length of the gap, since the teeth also are long; or, say, 15 inches. The actual length was 18 inches. The principal data being thus accounted for, it will now suffice to add the following data as given by Mr. Parshall.

Net iron-length of armature core-body 14·9.

Internal diameter of armature-core 71.

Yoke (cast-steel), internal diameter 138·25.

Yoke, external diameter 149·6.

Yoke, diameter over ribs 157·5.

Yoke, length parallel to shaft 24.

Number of equalizing rings 10.

Number of equalizing points per ring 5.

Pitch of winding is over 29 teeth.

Armature-spider has 5 arms, with 15 dovetail notches to receive cores.

Style of winding, lap-wound, barrel-drum.

Average volts per segment of commutator, 6·1.

Breadth of carbon-brushes 1 inch, or 3 segments.

Amperes per square inch brush-contact 40.

Shunt-wire makes 1154 turns per bobbin, and consists of 780 turns No. 9 B. and S., and 374 turns No. 10 B. and S.

Voltage-drop at full-load is as follows:—12·6 volts due to copper armature resistance (at 60° C.); 2·4 volts due to brush contacts; 0·6 due to resistance of the compound winding; or in total 19 volts. Hence, to give 550 volts at terminals, the internal electromotive-force generated at full-load must be 569 volts; which, assuming speed constant, means that the armature-flux at full-load must rise to 20,360,000 lines per pole. Assuming a dispersion ratio of 1·125, this makes the values of the flux per pole in the pole-core 20·8 megalines at no-load (500 volts) and 23·6 megalines at full-load (550 volts).

The excitation is given by Mr. Parshall as follows :—

—	B No-Load.	B Full-Load.	Amp.-Turns, No-Load.	Amp.-Turns, Full-Load.
Core-body	59,000	67,000	190	320
Teeth	108,000	119,000	340	900
Gap	42,500	48,500	5000	5700
Pole-core	78,000	88.000	880	1530
Yoke	69,000	79,000	640	1000
		Totals . .	7050	9450

There are 180 conductors on the armature per pole, each at full-load carrying 100 amperes, making 18,000 armature ampere-conductors per pole, of which about 20 per cent., or 3600, are demagnetizing, and about 80 per cent., or 14,400, are cross-magnetizing. Total ampere-turns allowed for on each magnet-pole at full-load at 550 volts 12,350.

The heat-waste in iron in the armature was estimated at 0·88 watts per pound; hence, as core weighs 12,600 lb., core-loss was 11,000 watts. Armature resistance, brush to brush, at 60° C., 0·0125 ohm. Hence C^2R loss for 1000 amperes was 12,500 watts. Total armature loss 23,500 watts. Peripheral radiating surface 12,000 square inches; therefore 1·97 watts per square inch. Observed rise of temperature after 8 hours' run at full-load, by thermometer 26° C., by resistance 38° C. Excitation losses: total C^2R loss per bobbin, at 60° C., 422 watts. External cylindrical radiating surface of 1 bobbin 1350 square inches; therefore 0·312 watts per square inch. Observed rise of temperature after 8 hours' run at full-load, by thermometer on surface of shunt coils 26° C., by resistance 45° C. C^2R loss at brush contacts 2400 watts; in commutator segments 400 watts. Friction loss at commutator 870 watts. Total watts lost in commutator 3670; radiating surface 2400 square inches; therefore 1·53 watts per square inch. Observed rise of temperature after 8 hours' full-load run, 22 deg. Centig. This makes the total losses as follows:—armature 23,500, field-magnets 4220, commutator 3670; total 31,390 watts. Hence the efficiency (excluding friction at bearings) is 550 ÷ 581·39 = 0·945 = 94½ per cent. Assuming a permissible temperature-rise (by thermometer) of 30 deg. Centig., Parshall gives the following handy rules as to the requisite amounts of radiating surface:—

—	Armature.	Field-Coils.	Commutator.
Radiating surface (sq. in.) necessary per kilowatt output of machine.	18·75	15	3·75

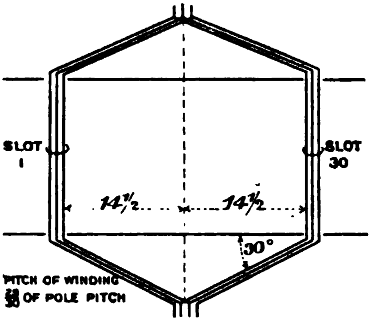


FIG. 437.—WINDING DIAGRAM OF PARSHALL'S 550-KILOWATT GENERATOR.

For some further tests made by Hobart on the various reactions of this machine, see *Electrical Review*, vol. l. p. 456, Mar. 21, 1902.

Constructional data of a larger General Electric Co.'s generator, M P 14—1000—100—575 volts—1740 amperes, are given by Hobart in an article in the *Elektrotechnische Zeitschrift*, xxii. p. 650, August 1901, where they are compared with those of kindred machines of equal output by Rothert, and by Siemens and Halske (Vienna), see p. 699.

One of the largest continuous-current machines is the

2700 kilowatt generator, with 36 poles, running at 75 revolutions per minute. It is over-compounded to give 525 volts at no-load, and 575 volts at the full-load of 4695 amperes.

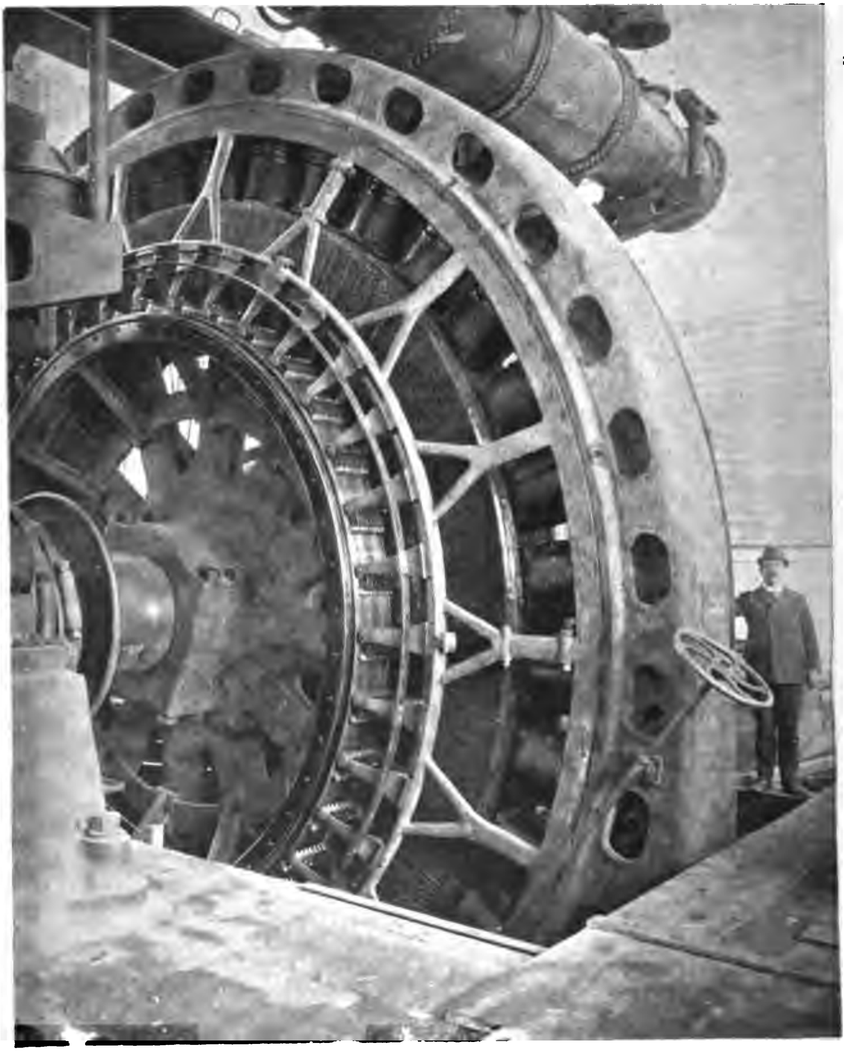


FIG. 438.—GENERAL ELECTRIC CO.'S TRACTION GENERATOR, M P 36—2700—75.

Fig. 438 shows a view of this machine as completed at Boston, Mass.

The armature of this machine is 260 inches in diameter, and the length of its core 16 inches. The armature spider is of cast-iron, with grooves to receive the dovetail projections of the laminations. The spider is designed so as to act as a fan and force air through the ducts in the core. The armature winding is of the barrel-type, with equalizing rings at the back. Armature coils are made in halves, with soldered connexions at the back. The commutator, 187 inches in diameter, is supported on an extension of the armature spider. The carbon brushes bear on the commutator not quite radially, but are slightly inclined forward to permit of freest movement in the guides. The magnet-frame is of cast-iron, divided horizontally to admit of inspection. Each half was in fact constructed in three separate pieces to facilitate transportation. The magnet-cores are of cast-steel, fitted with laminated pole-pieces ; the latter being composed of laminations of two different lengths so as to produce a graduated fringe. The pole-cores are secured to the yoke by screws. The coils are wound on bobbins having a body of double sheet-iron, with flanges of malleable iron. The shunt winding is next the yoke, the series winding next the pole-face.

The following is the guarantee on this machine :—The insulation between the field-coils and magnet-frame, and that between the armature-winding and the armature-core, must be capable of withstanding the application of 4000 volts, alternating, for 10 seconds, or 2000 volts for a duration of 60 seconds. The temperature rise after a run of twenty-four hours at full-rated load must not be more than 35° C., nor more than 55° C. with an overload of 50 per cent. for two hours, following a run of twenty-four hours at normal full-load. It must carry an overload of 50 per cent. at rated voltage, for two hours, or a momentary one of 100 per cent., without movement of the brushes and without injurious sparking. The weight of the armature is 160,000 lb., and that of the entire machine, 310,000 lb.

Plate XIII. illustrates a tramway generator constructed in 1900 by the Aktien-Gesellschaft Elektricitätswerke (formerly Kummer & Co.) of Dresden, designed by E. Fischinger. This is M P 18—880—90; giving 1550 amperes at 570 volts. It is designed as a fly-wheel machine. The armature is 217 inches in diameter, with a core length of 15 inches. The commutator is 142 inches in diameter with 6·7 inches length of face. A point of interest in the construction is the magnet-pole, the shoe of which is composite, consisting of a forward-horn of cast-iron and a hindward horn of cast-steel meeting obliquely; the form adopted being intended to diminish magnetic distorsion at full-load. The narrow neck of cast-iron becomes highly saturated at no-load, so that as the excitation is increased at full-load, the flux through the hindward part of cast-steel shall not be shifted by the cross-magnetizing reaction of the armature. Another feature is the very short length of pole-core.

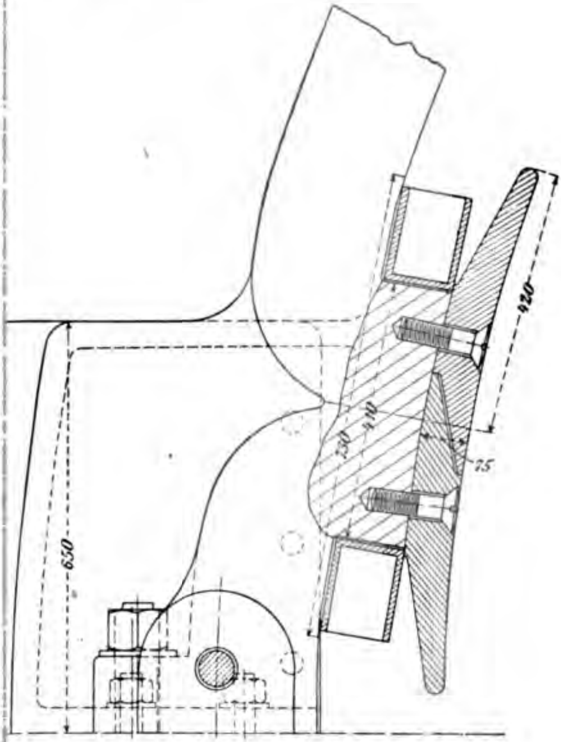
Plate XXII. depicts a lighting generator of the firm of Postel-Vinay of Paris, M P 16—400—70, giving 3000 amperes at 132 volts. This is one of the few large machines constructed with a ring-winding. The plate shows how the core-disks, built up in segments, are held by dovetail notches to projecting supports screwed into a rim which is itself bolted to the arms of a spider. The commutator shell is bracketed to the spider arms. One interesting point in construction is the absence of any outer bearing, the armature spider being keyed to the projecting end of the engine-shaft, with a bearing behind the armature. The design of this bearing, with the peculiar arrangements for centring, is shown in the Plate. It is due to Messrs. Farcot Frères, the constructors of the engine.

The following are the principal dimensions of this machine:—Armature diameter, 122 inches; armature core length, 19·7 inches; number of slots, 882, each 1·18 inch deep and 0·66 wide. Each slot contains side by side 2 conductors of dimensions 0·79 by 0·158 inches. There are 450 ampere-conductors per inch of periphery. The gap is 0·394 inch. Each pole is wound with 139 turns of a wire 0·336 inch in diameter. The over-all diameter of the yoke is 170 inches.

GENERATOR (DRESDEN).

CONSTRUCTED BY THE
ELLSCHAFT ELEKTRIZITÄTSWERKE
(FORMERLY KUMMER & CO.).
NED BY ENGINEER FISCHINGER.

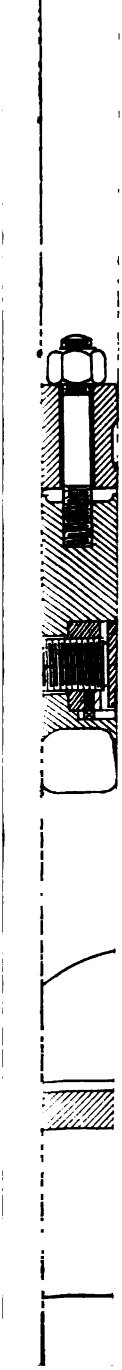
B-880 KW.-90 R.P.M.-570 V.-1550 AMP.
SCALE 1 : 40



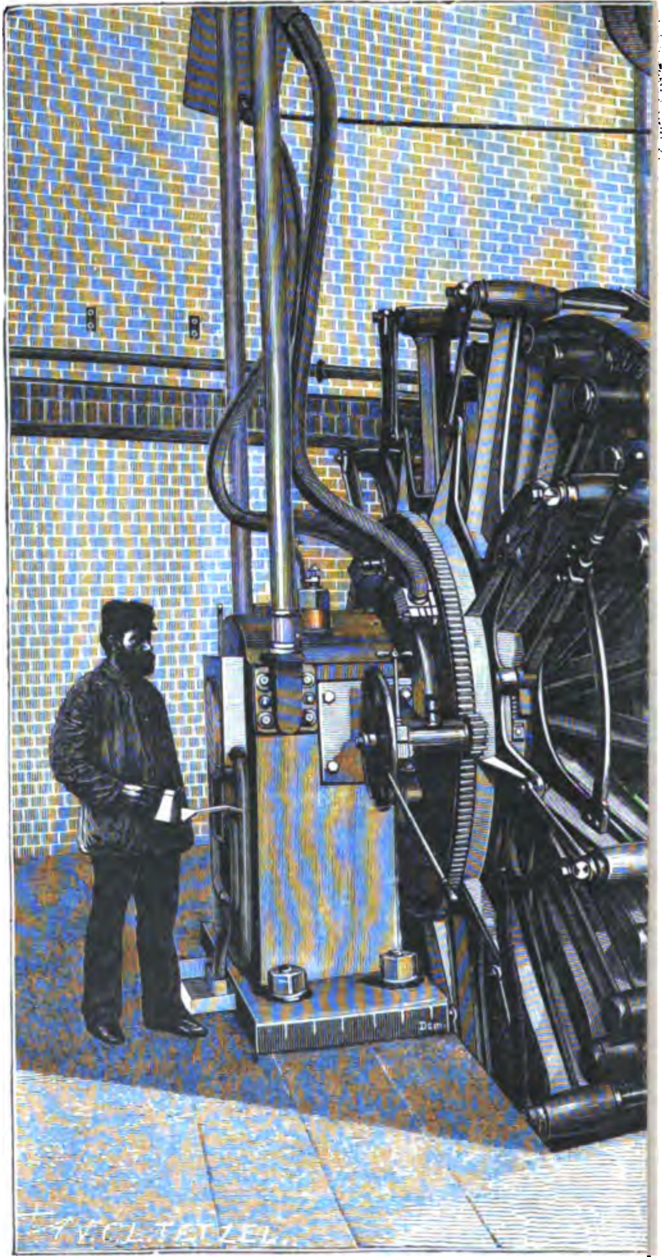
COMPOSITE POLE-SHOE,
sisting of a forward horn of cast iron and
ndward horn of cast steel, meeting obliquely,
diminish magnetic distortion at full load.

ARII

ères.



DYNAMO-ELECTRIC MACHINER



MULTIPOLAR INTERIOR-POLE DYNAM
CONSTRUCTED BY SIEMENS AND

The commutator, which has 882 segments, is 71 inches in diameter, the segments being 15·8 inches long. The resistance of the armature is 0·0015 ohm, that of the 16 shunt coils in series 1·3 ohms. The full-load flux in the pole is 13,700,000 lines.

The firm of Siemens and Halske, after constructing the bipolar for many years, developed multipolar types for their large generators. About the year 1886, they, and independently the firms of Ganz and Fein, produced[1] the type known as "Innenpol Maschine," having an external overhung ring armature. In Plate XXV. is shown one of these machines, the largest made being those in the station at Schiffbauerdamm and other central stations in Berlin. The dynamos are mounted in pairs on the ends of the main shaft of a compound condensing-engine of marine type, by Kerchove & Co., of Ghent, giving 1180 indicated HP, at 75 revolutions per minute. Each dynamo is capable of giving 2000 amperes at 140 volts, at 60 revolutions per minute. The field-magnet has 10 salient poles, with rectangular cores fixed to an annular yoke-ring which is carried in a U-shaped support on the bearing. The exciting coils are all joined together in series, and connected in shunt to the armature. The armature is built of core-rings mounted on insulated arms, which project from a bronze star-wheel, thus overhanging the field-magnet. Fig. 341, p. 464, shows the detail of construction. The winding, as that figure shows, consists exteriorly of straight copper bars, united by other pieces of bent form which pass through the inside of the ring from the end of one straight bar to the beginning of the next, thus constituting a spiral and endless winding. The collecting brushes trail against the exterior of the periphery of the armature itself, which thus serves as commutator and is 9 feet in diameter.

The brush-holders are mounted on a stellate rocker, shown separately in Plate XXV., and are provided with means to lift them all simultaneously off the commutator.

---

[1] See *Elektrotechnische Zeitschrift*, April and May, 1887; *La Lumière Électrique*, xxiv. 182, 1887; and *Centralblatt für Electrotechnik*, ix. 186, 410 and 581, 1887.

On Plate XXV. is also shown a more recent generator, M P 12—910—180, with external field-magnet.

Fig. 439 depicts a more recent machine of Siemens and Halske, giving 300 amperes at 500 volts, at 400 revolutions per minute. The armature has 166 slots, each 32 mm. deep by 9 mm. wide. The conductors are shaped on a former and lie in two layers as a barrel-winding. The section of the conductors is 6 × 12 mm. The armature-resistance is 0·0211 ohm. The commutator has 166 segments. The shunt-winding has 1965 turns on each pole, the wire being 1·94 mm. in diameter, and its total resistance 100 ohms.

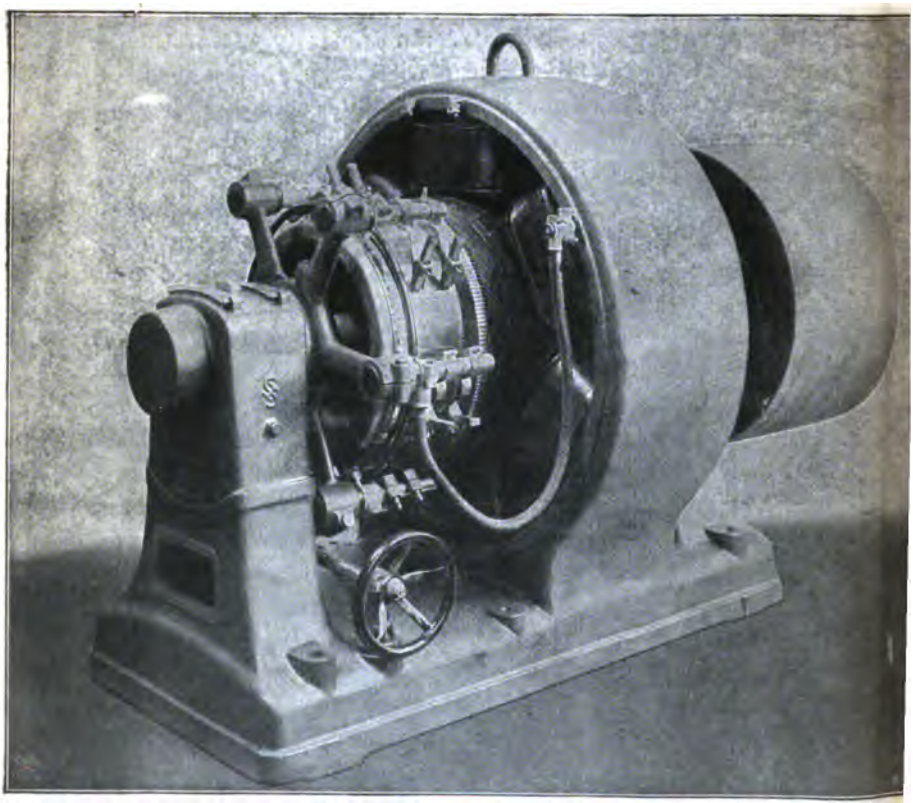
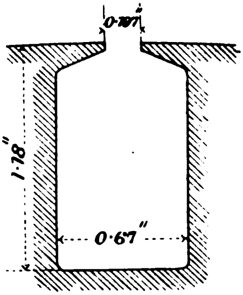
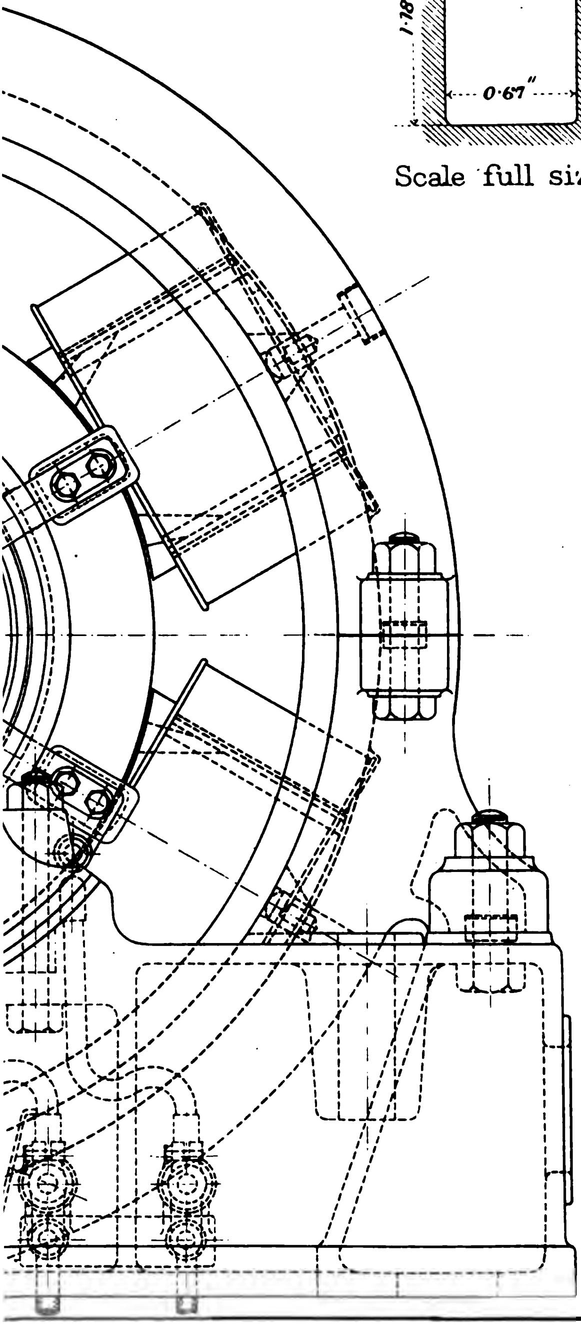
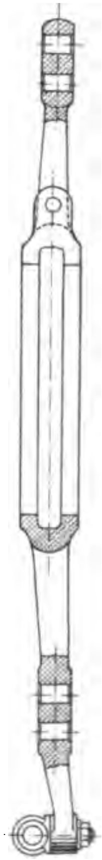


FIG. 439.—SIEMENS AND HALSKE GENERATOR, M P 6—150—400.



Scale full size





Thos Kell & Son. Lith

Plates XXII. and XXIII. relate to a dynamo constructed by Messrs. Ganz & Co. on their type for marine lighting, M P 6—64—320, giving 170 amperes at from 330 to 400 volts. The striking feature of this machine is the comparatively small number of slots in the core-disk, there being only 47 in the 6-pole machine. This would lead to trouble from the distortion of field and production of eddy-currents in the poles, were it not for the special arrangements of the latter. As may be seen from Plate XXIII. the pole-cores are built up of stampings held by a dovetail to the yoke. The stampings themselves are of three different shapes, assembled so that those with extended tips, only one-fourth of the whole number, will become highly saturated, and present a well gradated fringe of field. The arrangements of the commutator are very substantial. The following are the principal dimensions of this machine. Diameter of armature 21·9 inches; internal diameter of core 12 inches; core length 11 inches; ducts 4, each about ¼ inch wide; core-sheets 20 mils thick. There are 47 slots each containing 10 conductors. The slots are 0·67 inch wide, and are narrowed at the top to 0·157 inch. The total depth of slot is 1·18 inches, but the projecting tips of the teeth reduce the working depth to about 1 inch. The tooth-pitch is 1·462 inches, and the width of tooth at the face 1·305 inch; at the root its width is only 0·59 inch. The conductor, of strip copper, is 0·434 × 0·098 bare, or 0·454 × 0·118 inch covered. The winding is a series-parallel having two circuits. The winding-pitches are unequal, $y_1 = +77$, and $y_2 = +79$. Hence, $\bar{y} = 78$, and $p\bar{y} + c = 6 \times 78 + 2 = 470$. The gap is only 3 mm. = 0·118 inch, an impossibly small amount were it not for the careful lamination of the poles. The length of pole-face, parallel to the shaft, is 10·2, and the pole-arc 8·66 inches. The length of the pole-core is about 7 inches. The diameter of the commutator is 15·8 inches, the working length 4·14. This would be impossibly short, but for the use of reaction brush-holders (p. 509), which enable the two carbon brushes to cover nearly the whole length of the working face. There are six brush sets. The commutator has 235 segments. The mica-insulation is 20 mils thick. The yoke is of cast-steel. Each pole-coil is wound with 1360 turns of a wire 0·067 inch bare, or 0·087 covered. There are nearly 5 miles of the shunt-winding, and its resistance is about 60 ohms when warm. After a six-hour run the temperature rise was 41·5 deg. Centig. in the armature and 48 deg. Centig. in the field. The losses at full-load were about 5685 watts thus distributed: armature copper 2114 watts, armature iron 1257 excitation 1371, brush contact 486, brush friction and windage 457, total 5685. This, at 64 kilowatts output, makes the efficiency 92 per cent.

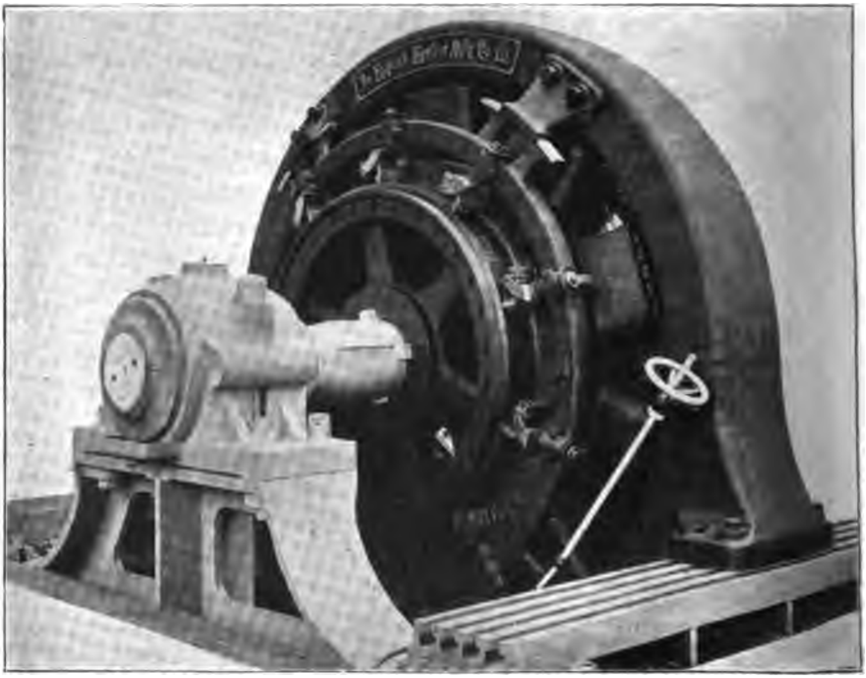


FIG. 440.—TRAMWAY GENERATOR OF THE ENGLISH ELECTRIC MANUFACTURING CO., PRESTON.

In the actual machines furnished for marine use, the voltage is usually only 120 to 130 volts, and they are fitted up as double-current machines with three slip-rings connected beyond the commutator so as to afford a three-phase current for motor driving, the continuous-current being used for lighting only.

The English Electric Manufacturing Company (Dick, Kerr & Co.), of Preston, produce a standard type of generator designed by the late Prof. S. H. Short, depicted in Fig. 440. A sectional view of a 12-pole machine[1] is given in Fig. 442. This is an 1100 kilowatt generator, running at 100 revolutions per minute. It has a heavy cast-iron yoke; the laminated pole-cores being cast in solidly, and a cast-iron pole-shoe attached by screw-bolts. Fig. 441 shows the laminated pole-cores. The pole-shoes, as will be seen from Fig. 442, which gives a view of a magnet-frame, are in two halves, being

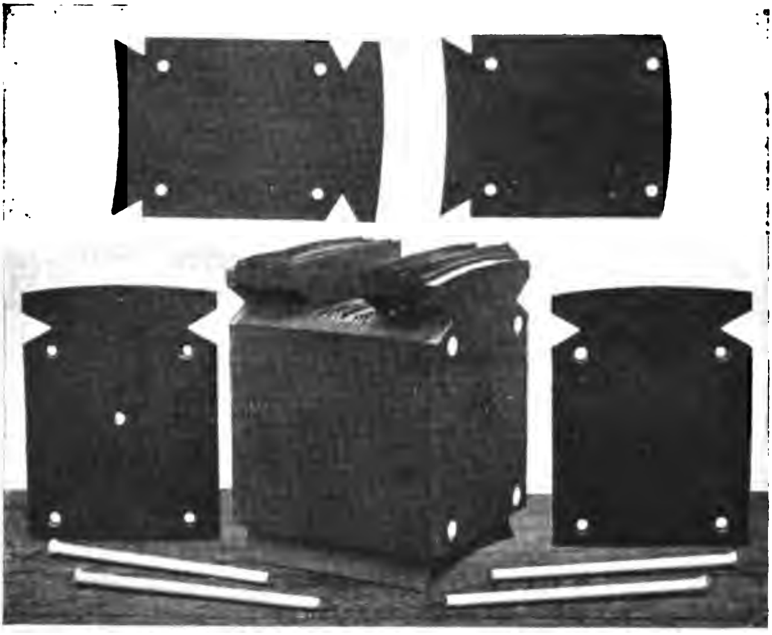


FIG. 441.—POLE-CORE STAMPINGS.

---

[1] See *Engineering*, Jan. 24, 1902, p. 118.

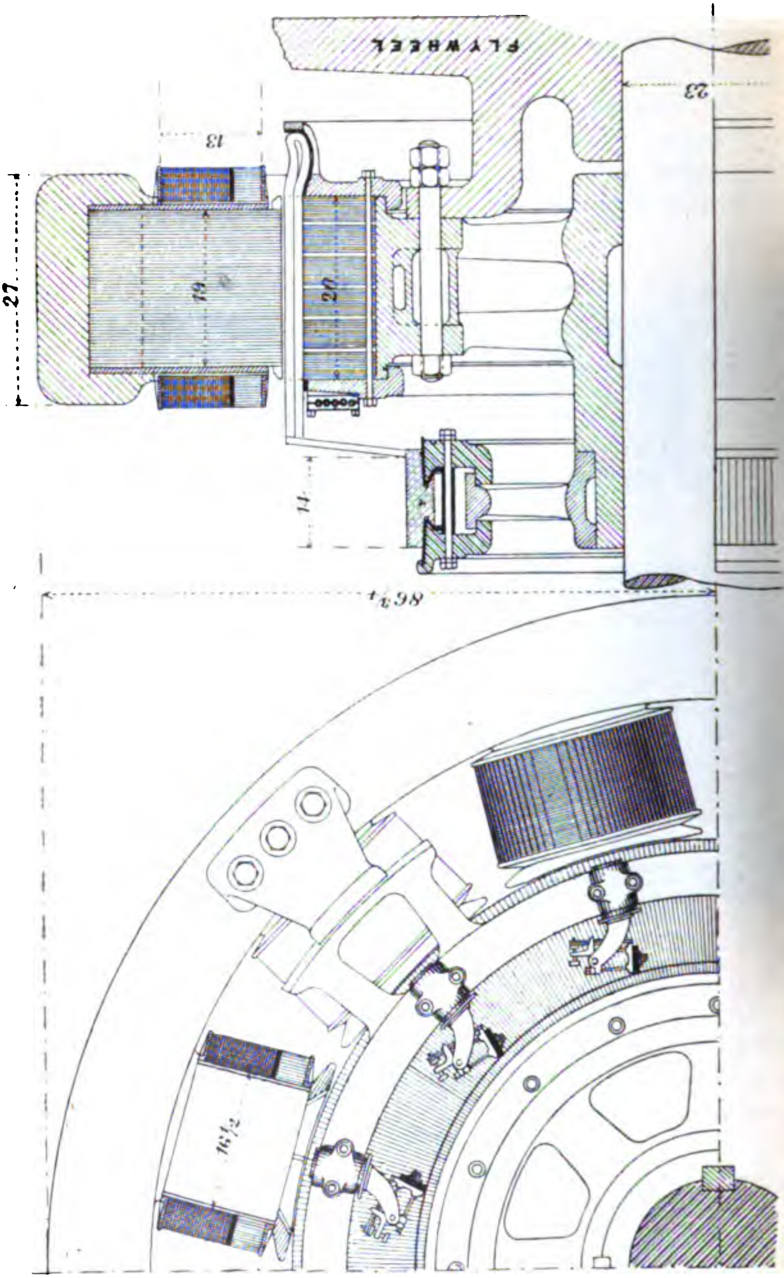


FIG. 442.—SECTION OF ENGLISH ELECTRIC MANUFACTURING CO.'S GENERATOR, M P 12—1100—100.

secured in V-notches punched in the laminated pole-cores, the two halves being clamped together by bolts, a space being intentionally left between the two halves to assist in preventing distortion of the pole-face flux. In order to secure a well-graded fringe at the pole-tips they are notched, as is well shown in Fig. 443.

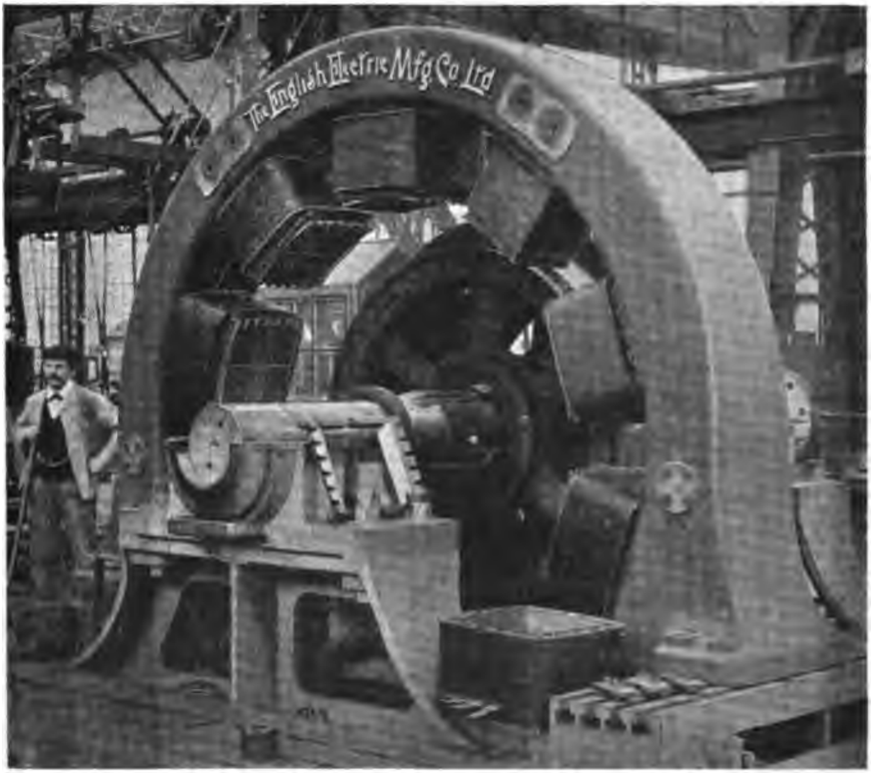


Fig. 443.—Magnet-Frame of 10-pole Machine.

The construction of the shunt-bobbins is shown in Fig. 444. The bobbins have cast-metal end-plates cast in open design, to render the ventilation as good as possible. The shunt and compounding turns are wound side by side and not in superposed layers as is usual. The compounding turns are wound edgewise, of copper strip.

The armature is a simple lap-winding, each element being a loop of strip copper in one piece. Fig. 445 shows the complete armature-core. Equalizing rings, or connexions short circuiting points of the winding at approximately equal potential, are used to facilitate commutation; and their arrangement is plainly shown in the figure, between the commutator risers and end-plates of the armature.

Fig. 277, p. 424, shows the core-plates of this machine, and the process of manufacture, from the blank (numbered 1 in the figure) to the complete section (numbered 4). One of the core-plate separators to keep the laminations apart for the formation of ventilating ducts is also shown (numbered 3).

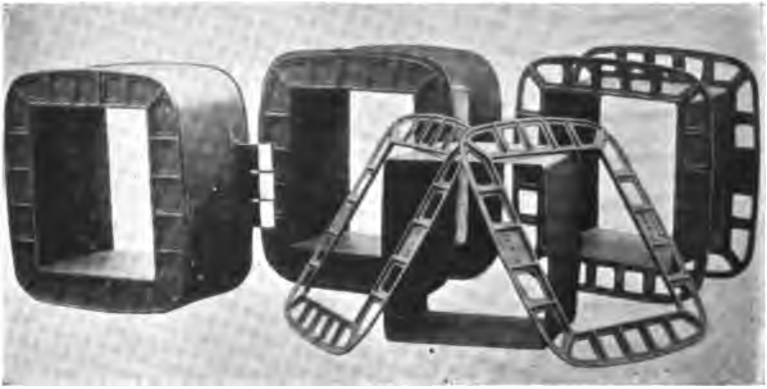
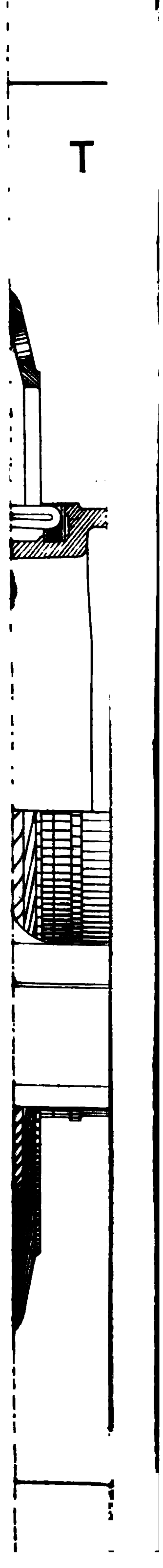


FIG. 444.—FIELD-MAGNET BOBBINS.

Fig. 298, p. 434, shows the armature-spider ready machined. It has six arms, with dove-tail grooves for holding the core-plates. The commutator seating is plainly shown, as also the seatings and bolt-holes for securing the commutator to the spider. The method of assembling the segmental core-plates was shown in Fig. 299, p. 435.

The brush gear was depicted in Fig. 380, p. 512. The brush-rocker is carried on a massive cast-iron ring, which is bracketed out from the yoke, as is shown in Fig. 440, a worm-wheel being used to shift the rocker for adjustment of the brushes.


T

A generator by the International Electrical Engineering Company, of London, is shown in Plate XXIV., M P 8—450—250—500 volts—900 amperes, having cast-steel poles cast in one piece with the yoke. It has laminated pole-shoes bolted on after the shunt-bobbins are placed in position. The outside diameter of yoke is 91 inches, radial length of pole-core 15 inches, and the bore of field is 49·7 inches, and the armature being 49 inches in diameter, the length of air-gap is about 0·35 inch. The total flux from one pole at no-load is 20·15 megalines, and as the area of pole-face is about 280 square inches, the pole-face density is about 73,000 lines at no-load, which is rather high. In this machine in fact both the magnetic fluxes and current densities are pushed as high as possible, but a fairly high armature surface speed, combined with careful design as regards ventilating capabilities, enables this to be done, without excessive heating. There are 1350 turns on each field-bobbin, and the poles being circular the mean length of one turn is 58·6 inches; the shunt-winding space is 11·5 inches in length and the wire is wound to a depth of 2·75 inches.

There are 200 slots and 800 conductors 0·118 inch by 0·443 inch, and consequently there are four conductors per slot, the slots being 0·394 inch wide and 1·18 inch deep. The winding has eight parallel circuits and eight sets of brushes. The armature has three ventilating ducts and the stampings are held by two substantial end-castings bolted on to a spider of simple design. The commutator is bracketed out from the main armature-spider, being secured by screws; the diameter of the commutator is 33 inches and the segments are 12½ inches over all.

Mr. H. M. Hobart, who has written on dynamo construction in conjunction with Mr. Parshall, has contributed to the subject of dynamo design a paper[1] in which he gives particulars of a large number of machines of his own designs. Amongst these is noticeable a large generator, M P 22—1600—85—550 volts—2900 amperes, which has the high peripheral speed of 4000 feet per minute and the remarkably low Steinmetz coefficient of 1·44, showing great economy of material. The chief data of this machine are as follow :—

---

[1] *Journ. Inst. Elect. Eng.*, vol. xxxi. p. 170, 1901. See also some articles by Hobart in *Electrical Review*, vol. l. pp. 329 *et seq.*, February and March 1902.

Armature :—

Core-disks, external diameter (inches)	177
,, internal ,, ,,	148
Number of slots	440
Depth of slot (inch)	1·34
Width ,, ,,	0·55
Pitch of slot at armature face (inch)	1·26
Depth of iron in core, under teeth (inches)	13·36
Gross length of core (inches)	13
Iron ,, ,, ,,	8·6
Diameter of finished armature (inches)	177
Number of conductors	2640
Arrangement	6 in a slot
Style of winding	parallel (lap)
Dimensions of each conductor, bare (inches)	0·53 × 0·118
Section of each conductor (square inch)	0·0625
Minimum width of tooth	0·735
Number of ventilating ducts	7

Field-Magnets :—

Diameter of bore (inches)	177·79
Pole arc ratio (per cent.)	72
Diameter of magnet-core	15
Length of ditto	19·18
External diameter of yoke (inches)	254
Gap	0·394
Flux in magnet-cores (megalines)	17
Flux density in pole-cores (steel)	97,000
,, in gap at pole-face	64,000
,, in yoke (steel)	35,000
,, in teeth (apparent)	148,000
,, in core-body	63,000

Commutator :—

Diameter (inches)	138
Number of segments	1320
Active length (inches)	9·6

Other data are as follows :—

Current density in armature conductor	2128
Space-factor of slot	0·51
Average volts per segment of commutator	9·2
Current density in brush face	32·2
Armature ampere-turns per pole	7900
Amperes in one conductor	132

Ampere-conductors per inch peripheral	627
Ampere-turns per pole at no-load	13,000
„ „ „ „	16,000

The losses are as follows at full-load :—

Armature iron loss (watts)	32,000
„ copper loss	24,400
Commutator resistance loss	5,800
„ friction loss	5,300
„ stray losses	300
Excitation, shunt	13,000
„ „ rheostat	2,000
„ series	3,000
„ „ diverting shunt (see p. 531)	1,000
Total	86,800

Total constant losses	52,600
„ variable losses	34,200
Commercial efficiency, full-load (per cent.)	94·9
„ „ half-load	92·8
„ „ quarter-load	88·1

The number of watts wasted per square inch of peripheral surface with a temperature-rise of 60° C. was 3·9 in the armature, 2·4 in the commutator, and 0·58 in the magnet-coils.

The core stampings weighed 7·7 tons, the armature copper 1·1 tons, commutator segments 1·7 tons, the magnet copper 2·7 tons, the pole-cores 10 tons, total magnet-yoke (with feet) 33 tons.

Another machine, MP 16—1000—90—500 volts—2000 amperes, described in the same paper by Mr. Hobart, and constructed by the Union Elektrizitäts Gesellschaft, for Sheffield, has been fully analysed on pp. 632 to 643.

Fig. 445 gives a view of a machine MP 8—300—150—$\frac{500}{550}$ volts—600 amperes, by the Electric Construction Company of Wolverhampton. The yoke is of soft cast-iron, and the pole-cores of sheet-iron stampings cast in; with soft iron forgings for pole-shoes screwed on. The armature-core is built up of charcoal iron stampings of 11 inches radial depth, assembled to a gross length of 15 inches including four air-ducts. It is clamped between cast end-plates, which have

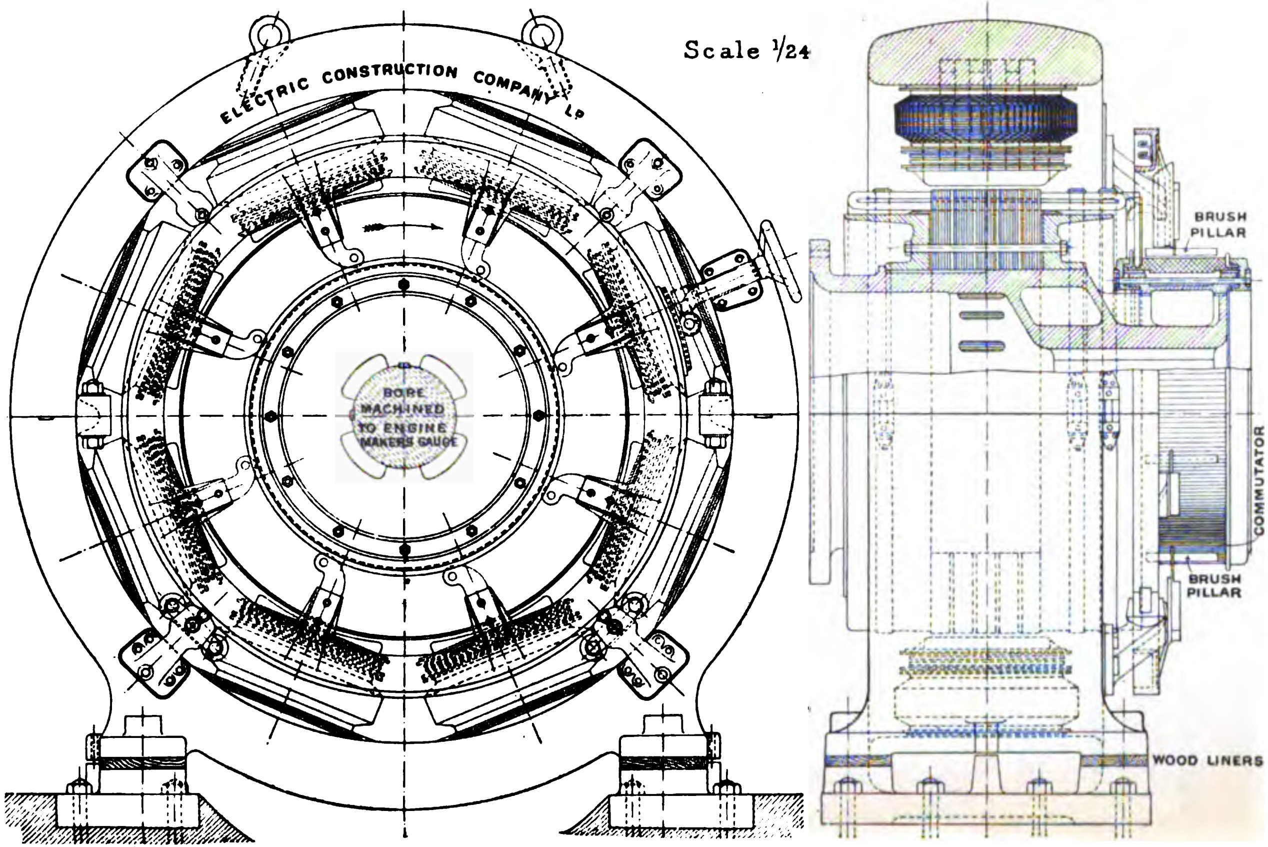

Scale 1/24
ELECTRIC CONSTRUCTION COMPANY LD
BORE MACHINED TO ENGINE MAKERS GAUGE
BRUSH PILLAR
COMMUTATOR
BRUSH PILLAR
WOOD LINERS

FIG. 445.—ELECTRIC CONSTRUCTION CO'S. 8-POLE 300-KILOWATT TRACTION GENERATOR.

brackets to carry the barrel-windings. The armature and commutator are mounted on a cast-iron spider keyed at the commutator end to the shaft, but expanded at the other end into a wide driving-flange that is bolted to the boss of the fly-wheel. On the inner part of the spider are cast oblique webs to serve as fans. The armature-winding consists of 1536 conductors of strip of a sectional area stated to be 0·0636 square inch. The commutator, which is 42 inches in diameter, with a working face 11½ inches long, has 768 segments. Each section of the winding consists of a single jointless loop bent edge-on at the end away from the commutator, and former-shaped. The external diameter of the armature is 62 inches. The slots have straight sides, and are lined with separate insulation. The insulation resistance is stated at 100 megohms, and the temperature rise after 8 hours' full-load run is stated not to exceed 28° C. The conductors are secured in the slots by wedges of hard wood, and by binding wires over the projecting ends. The rocker-ring runs on rollers bracketed out from the yoke, with an adjusting worm-wheel gear. The shunt-current at normal full-load is 8·3 amperes; the shunt-winding being former-wound with coned ends. The machine is over-compounded by 10 per cent., the full-load voltage rising to 550 volts. The series-winding is also former-wound, of rectangular strip, wound edge-on, of two flat spirals united together at the inner periphery, thus bringing both free ends to the surface. At full-load the series-winding takes up about 1·2 kilowatts, being therefore about 0·033 ohm in resistance.

A large traction generator constructed by Siemens and Halske, of Vienna,[1] was shown by this firm at the Paris Exhibition of 1900. Its type is MP 14—1000—95—550 volts, thus giving 1820 amperes at full-load. The armature has a diameter of 98·5 inches; the length between core-heads is 21·3 inches. There are five ventilating ducts, each about 0·4 inch wide. There are 1144 conductors, each 0·157 inch × 0·71 inch, and four of these conductors are placed in each slot, there being

---

[1] *Zeitschrift für Elektrotechnik*, vol. xviii. p. 551, 1900.

therefore 286 slots, the size of the slots being 0·51 inch wide by 1·97 inches in depth. The winding is series-parallel with 10 circuits. The commutator is 82 inches in diameter, with 572 segments, mica 0·031 inch thick being used for insulation between the segments. The minimum length of air-gap is 0·35 inch, and the maximum length 0·47 inch, the average flux-density in the gap being 58,000 lines. The yoke is of cast-steel, the over-all dimensions of the machine being 156 inches or 13 feet.

The fourteen field-bobbins have each 770 turns of wire, the ampere-turns at full-load coming out to about 18,500, the excitation required for this being about 13 kilowatts, or 1·3 per cent. of the full-load output of the machine. There are 14 sets of brushes.

The temperature-rise after 24 hours' full-load run is 30° C.

The total weight of the machine is just over 100,000 lb., or 44½ tons.

A detailed account of many other modern machines is to be found in C. F. Guilbert's book, *The Generators of Electricity at the Paris Exhibition of* 1900 (Paris, Naud, 1902).

Summary.—The machines which have now been described are summarized in the following Table in order to afford a view of the several values of the more important coefficients adopted in their design. The coefficients a and β in the later columns are explained on p. 576 above, and signify respectively the gross values of the average current-density and of the average magnetic density in the active belt at normal full-load. The values in the last column of kilowatts of output per cubic inch of the active belt are, like the preceding, deduced from the normal full-load output for which the machines are rated. All makers do not, it is well known, adopt the same basis for the rating of their machines, for some allow a higher temperature-rise than others. It is quite impossible to reduce the values to a common basis in this respect. Nevertheless the values given are not altogether unfair as a means of comparison. If in any machine the peripheral speed is high, there is necessarily a higher specific utilization of material.

And if in any machine in which this is high the a and β densities are also high, the output per cubic inch of active

TABLE OF SPECIFIC UTILIZATION COEFFICIENTS AND OTHER FEATURES OF DESIGN IN CONTINUOUS CURRENT GENERATORS.

Maker or Designer.	Specification.						Steinmetz Coefficient σ.	Current in one conductor C_1.	Ampere conductors per inch	Peripheral speed ft. per min.	$\frac{C \times Z}{c \times \pi d \times s} = a$	$\frac{\phi N}{\pi d \times l} = \beta$	Watts per cub. in. of active belt.
	type.	poles.	kw.	r.p.m.	volts.	amp.							
Brown-Boveri & Co.	MP	8	194	350	490	396	2·47	49·5	575	3860	302	27400	62·5
Electric Construction Co.	MP	8	300	150	500	600	3·1	75	592	2430	246	39500	43
English Elec. Manfg. Co.	MP	12	1100	100	550	2000	1·96	166	610	2830	390	51400	103
General Elec. Co.	MP	10	550	90	550	1000	3·95	100	595	2760	297	32700	44·4
Hobart . . .	MP	22	1600	85	550	2900	1·44	132	627	4000	467	47000	163
International Elec. Eng. Co. .	MP	8	450	250	500	900	1·96	112	585	3200	496	47500	140
Kolben & Co. .	MP	4	70	750	260	270	4·6	135	408	4600	399	18200	67·4
Kolben & Co. .	MP	10	250	125	550	455	4·35	114	475	2200	480	35600	74
Oerlikon Co. . .	MP	4	265	370	450	510	2·9	255	430	3860	365	29000	92
	MP	4	265	370	550	360	2·9	180	348	3860	340	33800	106
Oerlikon Co. . .	MP	10	165	110	280	590	4·48	59	660	2160	440	25000	46
Oerlikon Co. . .	MP	12	500	100	550	900	2·8	150	643	2640	544	37400	96
Scott & Mountain	MP	6	150	450	250	600	2·42	100	473	3885	296	37800	80
Siemens & Halske	MP	14	1000	95	550	1820	2·07	182	672	2460	310	50500	70
Walker Co. . .	MP	10	440	85	550	800	3·6	80	585	2000	336	40500	44
EXCEPTIONAL DESIGNS.													
Brown Boveri & Co. (High Voltage)	MP	4	20	700	1000	20	7·35	10	300	2740	273	25900	39
Kolben & Co. (Exciter)	MPX	10	38	75	150	254	13·4	127	516	660	437	34700	20
Oerlikon Co. (Electrolytic)	MPC	32	560	55	80	7000	5·1	228	447	2540	505	28600	71
Oerlikon Co. (Electrolytic)	MPC	6	285	450	190	1500	2·18	250	835	4200	580	24070	117
Thury (Electrolytic)	MPC	12	832	120	208	4000	3·15	333	435	3580	368	29100	78

belt, and therefore the output in proportion to weight and cost, will also be high. The 8-pole machine of the International Electrical Engineering Company, and the 22-pole machine designed by Mr. Hobart, are cases in point. The high specific values attained in these machines unquestionably indicate the way to future economy in design. Everything points to the adoption of high-speed steam-turbines for all steam-driven dynamos of large power. With such speeds as these machines entail, very high surface-speeds will be reached; and design must be modified to meet these conditions. Greater axial lengths and relatively smaller diameters of armature will be a necessity; while with the high commutator speeds carbon brushes cannot be used. Both these influences will render greater the difficulties of sparkless commutation, and make more needful than ever the most careful attention to the question of saturation of teeth and of pole-pieces, and the combating of armature distortion. But they will also bring about a higher specific utilization of material.

With the introduction of large gas engines and the commercial production of cheap gaseous fuel, it would seem likely that for all generators exceeding 1000 kilowatts, gas engines will be employed rather than steam engines, in case water-power is not available. This development will again influence dynamo design: and as is very evident, the dynamos of largest output are precisely those in which the best ventilation can be attained, and in which the highest specific utilization of electric and magnetic materials is possible.

CHAPTER XXI.

DYNAMOS FOR ELECTRO-METALLURGY AND ELECTROPLATING.

SPECIAL forms of continuous-current dynamo are needed for the work of electroplating, electrotyping, and the electrolytic treatment of ores and purification of metals. In general, low electromotive forces and very large currents are requisite, for the quantity of metal deposited in the bath depends upon the quantity of amperes of current only, and not on the number of volts of electromotive-force. And though a few volts are necessary to drive the requisite current through the resistances of the circuit, the number is in general small. To decompose water electrolytically requires less than two volts. To deposit metal in a bath in which the anode is of the same metal as the deposit requires usually a very small electromotive-force. In general, if too great an electromotive-force is employed, or if the density of current (i.e. the number of amperes per unit of area of kathode surface) is permitted, the metallic deposits will be uneven or pulverulent. All these circumstances point to the construction of dynamos having at most but four or five volts of electromotive-force, but so designed as to have an exceedingly low internal resistance. If, however, as in some processes where equal currents are wanted in a number of tanks, the tanks are placed in series, the voltage needed will be greater in proportion to the number of cells. For example, in Castner's process for making caustic soda by electrolysing common salt solution, each tank needs 2·3 volts, so twenty tanks in series will need 46 volts.

The first application to the purpose of electroplating is due to Mr. J. S. Woolrich, who in 1842 patented[1] this use of a magneto-electric machine. Woolrich's machine (Fig. 446), was multipolar, with eight separately wound coils clamped in a wooden disk, which revolved between the poles of four large compound magnets. A primitive commutator enabled the machine not merely to rectify its currents, but to furnish an actually continuous current. This machine is now the property of the Corporation of Birmingham. This was, according to Sprague, the first practical machine for large currents and engine-power, and it gave great pleasure to Faraday. It was adopted by Messrs. Prince and Son, and long did duty at the works of the Electro-Metallurgical Company. The uniformity of the current evolved was considered remarkable. Shaw, in his *Manual of Electro-Metallurgy* (1844) states: "Mr. Sturgeon appears to be the first who deposited metals by this apparatus, but his experiments were on a small scale; and it is to Mr. J. S. Woolrich, of Birmingham, that the art is indebted for the perfection of the magneto-electric apparatus, and the development of its extraordinary

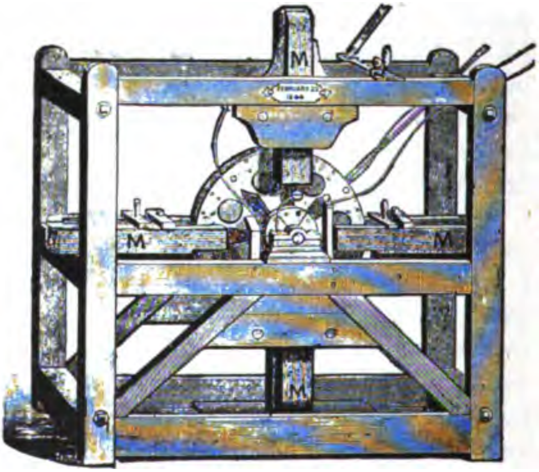


FIG. 446.—WOOLRICH'S ELECTROPLATING MACHINE.

---

[1] Specification No. 9431 of 1842.

power as an electro-metallurgical instrument." One of Woolrich's machines continued in use at Messrs. Elkington's establishment [1] for over 20 years. The principle of separate excitation of the field-magnets by a battery was patented by Wheatstone and Cooke in 1845. In 1860, Walenn again described the method of separate excitation, and in 1862 Monckton stated in his patent specification that the electromagnets used as field-magnets might be excited by a battery or other known source of currents. Millward, of Birmingham, showed that if a magneto-electric machine were employed to excite the coils of a larger electro-magnet, the amount of magnetism in the latter far exceeds that of the magnets in the exciting machine. Wilde, however, was the first to construct machines really fitted for the purpose, when he adopted the plan (previously proposed by Sinsteden) of concatenating machines. He used a large dynamo, the field-magnets of which were separately excited by currents derived from a smaller magneto machine. His first machines, which were used for many years by Messrs. Elkington,[2] were of the form shown in Fig. 6, p. 14. Both armatures were of the old shuttle-form, introduced by Siemens, and the larger one required to be kept cool by streams of water. After the announcement by Siemens and Wheatstone of the invention of the self-exciting principle, in 1867, Wilde introduced a multipolar machine with a rectifying commutator. Weston introduced a small machine for nickel-plating which had steel cores to the magnets but with main-circuit coils upon them, and an automatic cut-off to break the current, to prevent the magnetism from reversing by a back-current from the bath. Elmore built large dynamos, for copper refining, with eighteen electromagnets in each crown, yielding a current of 3000 amperes at a potential of seven to eight volts. Such a machine would deposit over 25 lb. of copper per hour. The field-magnet coils were unfortunately in series with the main circuit. All electroplating dynamos should be shunt-wound or they are liable to reverse their polarity. Gramme in 1873 built special forms of very low resistance with strip-wound armatures having a commutator at each end, and giving 1500 amperes at 8 volts. Siemens and Halske also were early in the field with machines having bar armatures, which they employed at their electrolytic works at Oker.[1] Brush also constructed large machines of low resistance for electroplating purposes. These machines had coarse wire coils connected in series, and a shunt, or so-called "teazer" coil, of finer wire to maintain the magnetism when the main circuit was opened; thus enabling the machine to do either a large or a small amount of work without fear of reversing the current. The voltage of this machine varied only from 3·3 to 4·1 volts, whilst the current varied from 300 amperes to zero.

---

[1] See also Napier's *Manual of Electro-Metallurgy* (3rd ed., London, 1857).

[2] For a further account of "Wilde's Magneto-electric Machine," see Watt's *Electrodeposition* (1886), p. 25.

Other dynamos have been designed for electroplating and electro-metallurgical work by nearly all the important manufacturers.

In dynamos for such purposes the requirement of large current and very low voltage introduces difficulties into the design, for the voltage cannot be obtained low enough without having either very few convolutions on the armature, or else a weak field-magnet. Machines with weak magnets give trouble with sparking. Machines with few massive conductors and few parts in commutator give trouble in sparking, and are liable to heat from local eddy-currents. It is customary to employ several *independent* windings (see pp. 367 and 377), all put in parallel by brushes of special thickness.

In Chapter X. it was mentioned that the drop of potential at the brush due to contact-resistance is from 0·7 to 1 volt at each side, or from 1·4 to 2 volts on the whole machine, when carbon brushes are used. With hard carbons this figure may even be exceeded. Such a drop would be serious indeed in the case of low-voltage machines, such as are used for typing, plating and nickeling. Hence for such machines copper brushes are almost always used. With copper brushes the drop due to contact resistance is only about 0·3 on each side, or 0·6 volt on the whole machine.

---

[1] See *Elektrotechnische Zeitschrift*, ii. 54.

Sayers has proposed an ingenious device to enable currents to be taken from a machine at various voltages. The pole surfaces are subdivided by deep nicks, as in Fig. 447, thus providing several neutral points on the commutator at which brushes may be placed without sparking. Thus, for example, whilst the potential between the two main brushes may be 10 volts, an intermediate brush may be employed to divide this into 7½ volts for nickeling and 2½ volts for silverplating.

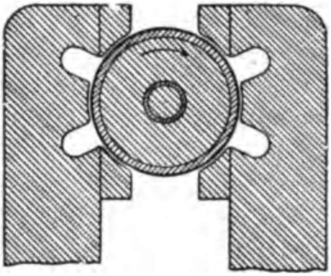


FIG. 447.—SAYERS' DYNAMO FOR ELECTROPLATING.

Messrs. Crompton & Co. have devised a method of dividing the main leads between two pairs of brushes touching adjacent bars of the commutator, and are thereby enabled to construct their plating-machines with fewer parts in the armature. The divided leads from the dynamo to the plating-tanks cost no more than a single undivided lead would do, but they interpose a comparatively large resistance in the path of the local current from the short-circuited section.

Some statistics relating to electro-metallurgy will be found in the Appendix to the present Chapter.

For some electro-metallurgical processes, dependent only on the generation of heat at a very high temperature, alternating currents may be used. Amongst such processes are those of the production of calcium carbide, the production of carborundum, the production of phosphorus, and the production of aluminium alloys in the Cowles furnace. But for others, involving electrolysis, the currents are necessarily continuous. Thus for the manufacture of aluminium, of sodium, of bleaching liquor, of chlorate of potash, and the like, as well as in the electrolytic treatment of ores, the refining of copper, and all processes for the deposition of metals, including typing and plating, continuous-current dynamos are necessary. For many deposition processes in particular a very low voltage is required, and unless the depositing vats are arranged in series the voltage of the dynamos is necessarily very low.

The machines therefore to be considered in this chapter may be grouped in two classes: (*a*) Electro-metallurgical dynamos ranging from 80 to 200 or 300 volts, and (*b*) Electrodepositing dynamos ranging from 2 to 10 volts. But to these must be added dynamos for charging batteries of accumulators for lighting, etc.; and these in general will have the same voltages as for direct incandescent lighting, and indeed differ in no essential from ordinary lighting dynamos.

The dynamos of classes (*a*) and (*b*) differ from the ordinary types used for lighting and traction in having to carry for the same kilowatt capacity a very much larger proportion load of amperes. Compare two machines of 1000 kilowatts, one for traction at 550 volts, the other for aluminium manufacture at 80 volts. Though requiring equal horse-power, one must carry a load of 1818 amperes; the other 12,500 amperes.

To collect 12,500 amperes from a dynamo requires extraordinary arrangements of commutator and brushes, and obviously, the armature copper must be designed with a total carrying capacity nearly seven times as great in the second machine as in the first.

The manner in which the adaptations of design necessary to solve this problem of collecting a very large current generated at a relatively low voltage are met in practice, may be studied by the aid of several modern examples.

For the special purpose of the aluminium industry several types of machines have been developed. Messrs. Crompton & Co. built a very large 2-pole drum machine,[1] capable of affording 5000 amperes at 60 volts. Mr. C. E. L. Brown[2] designed for the Oerlikon Works some 6-pole machines for 6000 amperes at 20 volts at 180 revolutions per minute. The armatures have each two separate windings with a commu-

---

[1] *Electrician*, xxi. 590, 1888; also *La Lumière Électrique*, xxx. 207, 1888.

[2] *La Lumière Électrique*, xxx. 205, 1888; *Electrician*, xxi. 727, 1888.

tator at each end, and at each commutator 36 brushes, arranged in six sets of six each. The field-magnet is like Fig. 13, but with six poles, and cast in one piece. The armature is 38 inches in diameter and 24 inches long. The windings were at first embedded in holes in the core-disks: but as troubles arose about insulation, the core-disks were turned down, and the armature re-wound with external conductors. Although there are as many brush-sets as poles, rendering cross-connection of the windings not absolutely necessary, yet such cross-connexions are added to ensure equalization of the currents, equipotential segments of the commutator being internally cross-connected by rings with three projecting lugs. Mr. Brown has also made some 8-pole machines for an output of 14,000 amperes at 30 volts.

Brown's Electrolytic Generator, MPC 8—480—250.—This machine, illustrated in Plates VII. and VIII., and in Figs. 403 and 404, is fully analysed as a design in Chapter XIX.

The *Oerlikon Machine Works* has produced many successful machines for electrolytic purposes. For the use of the aluminium industry Mr. C. E. L. Brown, at that time its chief designer, designed 6-pole and 8-pole dynamos. That depicted in Fig. 448 was a 300 H.P. machine working in the aluminium establishment at Neuhausen. This was the first dynamo of the vertical pattern designed to run upon a water turbine. With an average output of 3000 amperes the machine runs sparklessly. The mode of cross-connecting each part of the ring-winding to the two points of the commutator 45° distant is accomplished by bent two-legged strips of copper, as shown, serving as equalizers.

Fig. 449 depicts a 24-pole vertical shaft dynamo, designed in 1891 for the aluminium industry. The moving armature weighs 12 tons, and revolves at 150 turns per minute; total height, 12½ feet; total weight, 34½ tons. Its output is 7600 amperes at 55 volts; being about 600 H.P. To collect this current there are 24 ranks of brushes, 5 brushes in each rank, equi-spaced around a commutator 1·7 metres in diameter. The commutator is below the armature, which is drum-wound, having stranded conductors laid in perforations

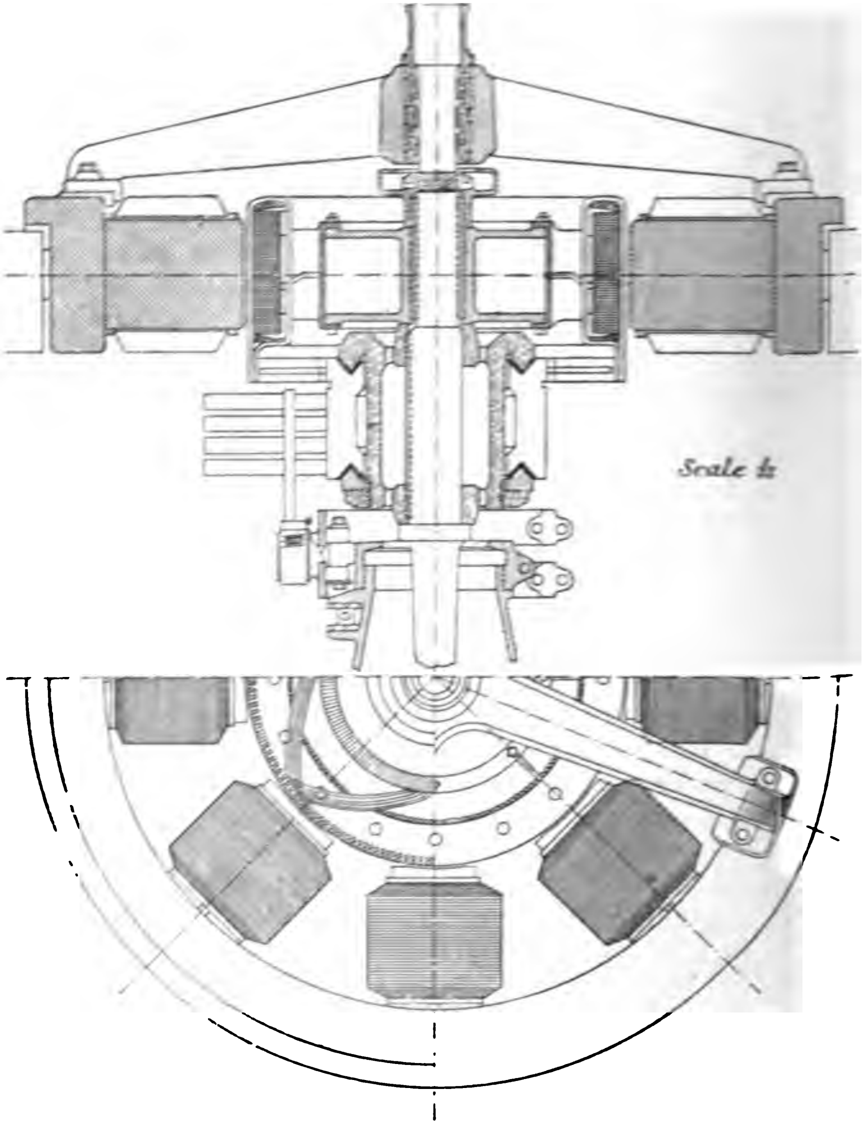


FIG. 448.—VERTICAL-SHAFT 8-POLE DYNAMO FOR USE WITH TURBINE (OERLIKON CO.).

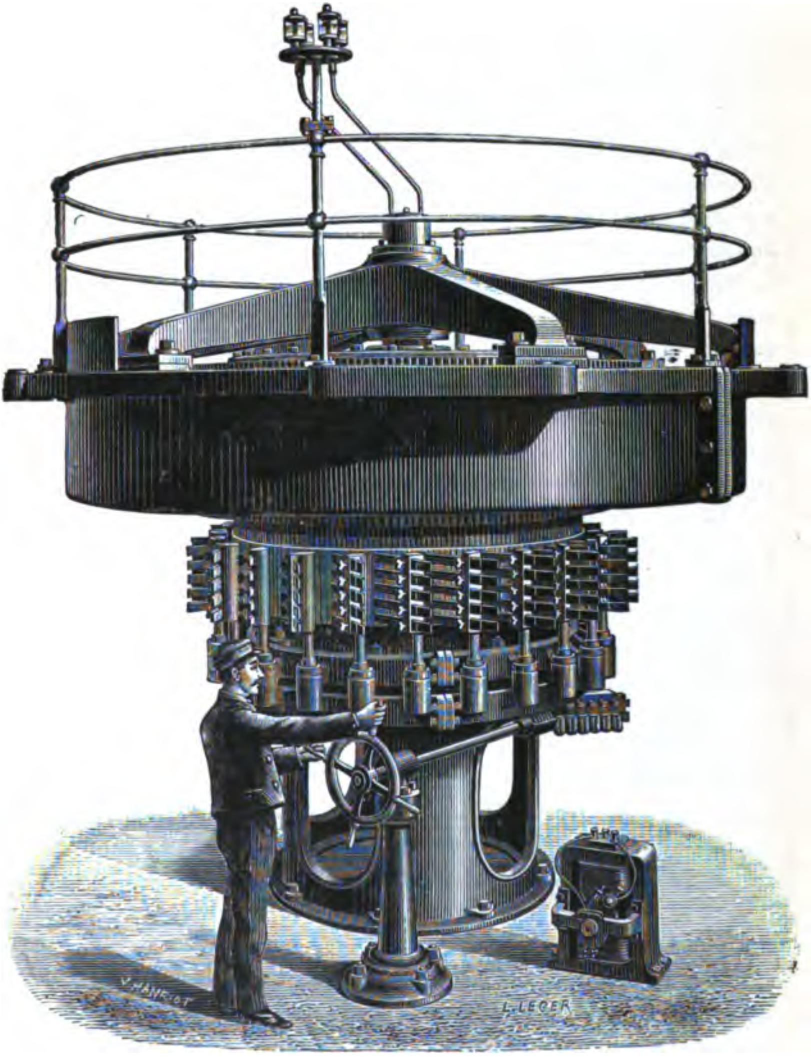


FIG. 449.—OERLIKON CO.'S DYNAMO FOR ELECTRO-METALLURGY.

through the core-disks. The field-magnet is constituted of a crown of 24 inwardly-pointing poles of cast-iron; it is supported upon a ring of masonry exterior to the machine.

Oerlikon Company's Machines.—A large electrolytic generator, furnished by the Oerlikon Company to the Aluminium Works at Rheinfelden, is shown in Fig. 450. In this machine MPC 32—560—55—80_{V}—7000_{A}, the very large number of poles is necessitated by the very large output and slow speed. To collect 7000 amperes with 32 brush-sets implies that each set must carry 436 amperes. The armature diameter is 177 inches, the length of its core 16·2 inches, making the Steinmetz coefficient 5·1. The pole-cores are cast solid with the yoke of steel; no pole-shoes being used. The armature is parallel-wound with 32 parallel circuits, so that the current in one conductor is 225 amperes; the end connexions at both ends of the armature are made of evolutes terminating in copper segments, held exactly as the segments in an ordinary commutator by end-clamping plates.

This construction enables a set of equalizing conductors to be added at the commutator end of the armature, as shown in the figure. There are 544 slots in the armature, there being two conductors per slot, each conductor having a cross-sectional area of 0·124 square inch, the slots being 0·885 inch in depth and 0·51 inch wide. The commutator is 118 inches in diameter, and has 544 segments, each segment being 13 inches in length; it is bracketed out from the armature spider. There are 32 sets of brushes with 12 brushes per set. The field-bobbins are connected in two parallels of 16 bobbins in series, each bobbin having 175 turns of copper wire 0·374 inch in diameter, wound in 7 layers of from 28 to 22 turns per layer. The flux per pole at no-load is 8·03 megalines.

Fig. 451 shows an Oerlikon generator MP 6—285—450—90 to 190 volts—1500 amperes, supplied to the Volta Electrochemical Company at Rome. See also Fig. 295, p. 432.

This machine has cast-steel poles bolted on, the pole-core and pole-shoe forming a single casting. The poles are slotted radially with a very large single slot about 4·7 inches long and 1·97 inches wide, this slot being, of course, provided to prevent distortion of the pole-face flux, this precaution being especially necessary in this machine, owing to

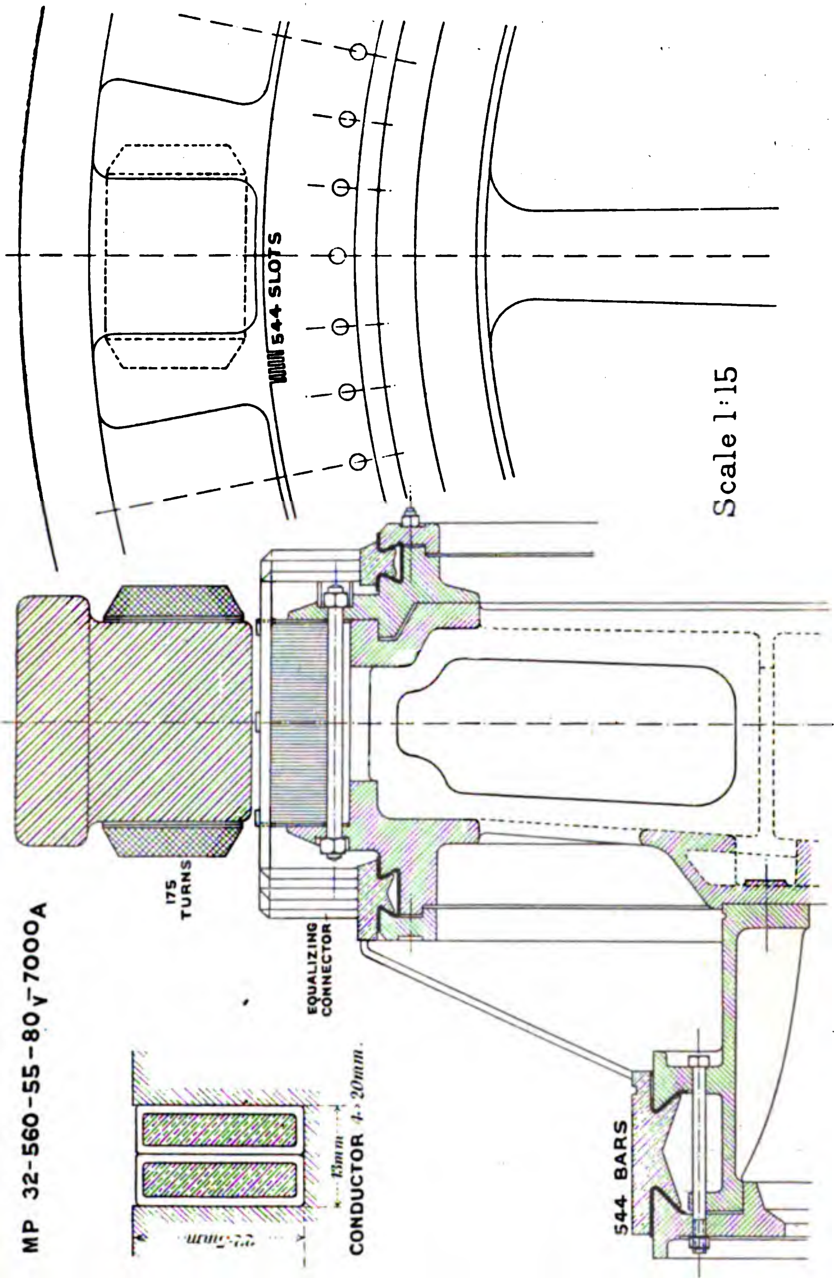


FIG. 450.—OERLIKON CO.'S 32-POLE VERTICAL SHAFT ELECTROLYTIC GENERATOR AT RHEINFELDEN.

the fact that very heavy currents are carried per unit length of periphery, the ampere-conductors per inch periphery working out to 835 at the full-load rated output of 1500 amperes; which is large for a 6-pole machine. The yoke is 62¼ inches in diameter over all; the armature is 35½ inches in diameter, and has 187 slots, each slot being 1·44 inches deep and 0 258 inches wide. There are in each slot two conductors of 0·093 square inch section, the current through each conductor being 250 amperes, there being thus 500 amperes to be collected at each set of brushes. The armature has a lap-drum six-circuit winding, the end loops of the former-made conductors being bent down and held in place

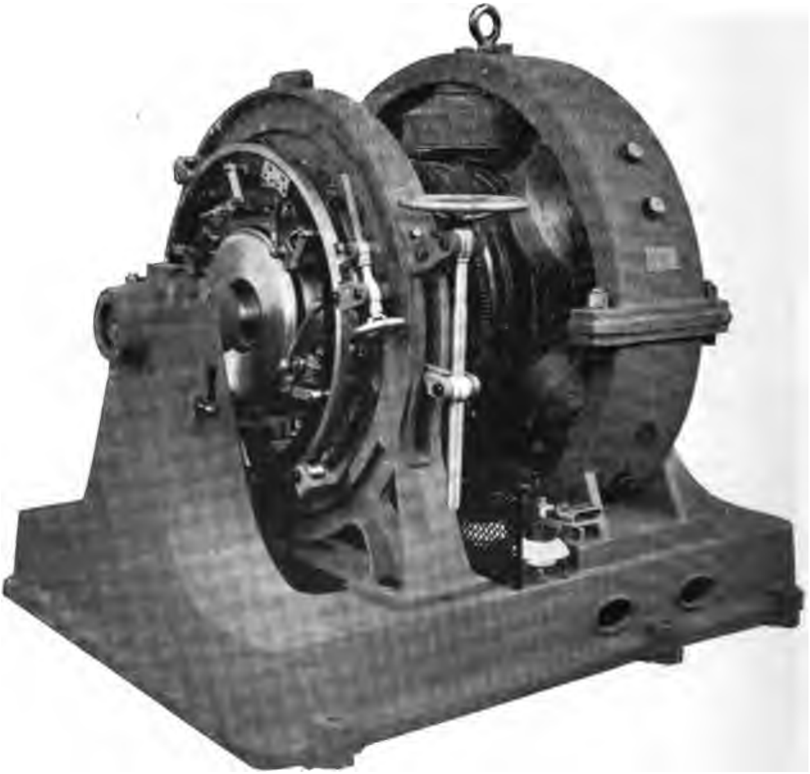


FIG. 451.—OERLIKON CO.'S 6-POLE ELECTROLYTIC MACHINE.

by an end-clamping shield. The commutator is 21 inches in diameter and of very massive construction, the segments being securely held at both ends and clamped in the manner plainly shown in Fig. 295, p. 432, which gives a section of the whole machine. The field-coils have each 600 turns of wire 0·189 inch diameter bare and 0·204 inch insulated. The brush-gear is held on an independent support rising from the bed-frame. It has two tangent screws; one to shift the rocker ring, the other to raise the brushes off the commutator simultaneously. It is illustrated in Fig. 452.

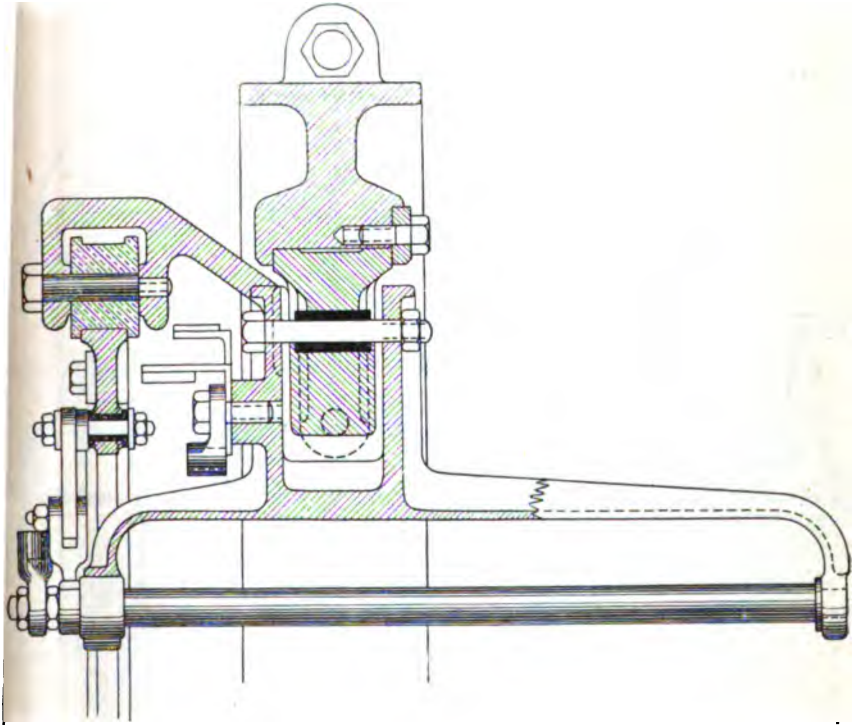


FIG. 452.—BRUSH PILLAR AND ROCKER FRAME OF OERLIKON'S CO.'S ELECTROLYTIC GENERATOR.

Plate XIV. illustrates one of the recent electrolytic machines of the Allgemeine Elektrizitäts Gesellschaft of Berlin, at work at Rheinfelden. It is a vertical shaft machine, turbine driven, having 14 poles. It makes 63 revolutions per minute, and gives 4300 amperes at 130 to 140 volts. To

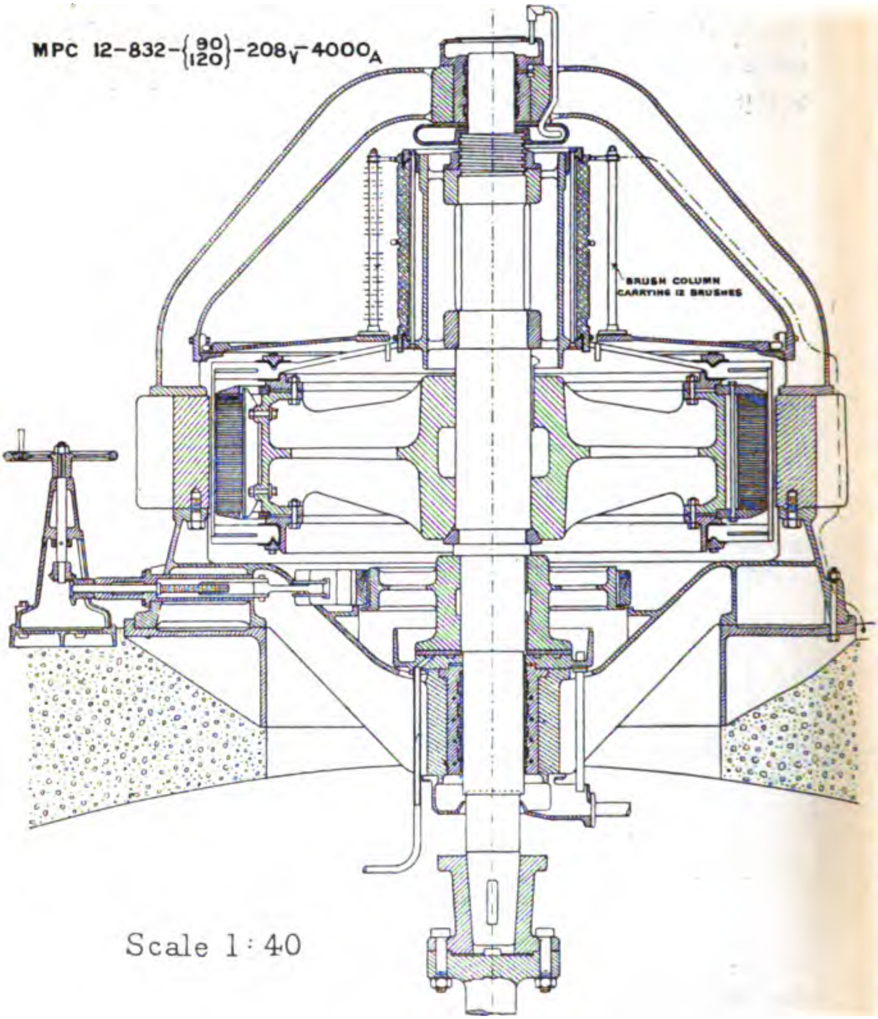

MPC 12-832-{90/120}-208V-4000A
BRUSH COLUMN CARRYING 12 BRUSHES
Scale 1 : 40

FIG. 453.—THURY'S ELECTROLYTIC GENERATOR : SECTION.

relieve the weight on the lower bearing it is lubricated with oil at a pressure of about 17 atmospheres.

Thury's Electrolytic Machines.—The firm known as La Compagnie de l'Industrie Électrique, of Geneva, has for many years constructed large machines for power and lighting as well as for electrolytic generators. One of the latter, MPC $12 - 832 - \begin{Bmatrix}90\\120\end{Bmatrix} - 208_{\text{v}}\ 4000_{\text{A}}$, is depicted in Figs. 453 and 454.

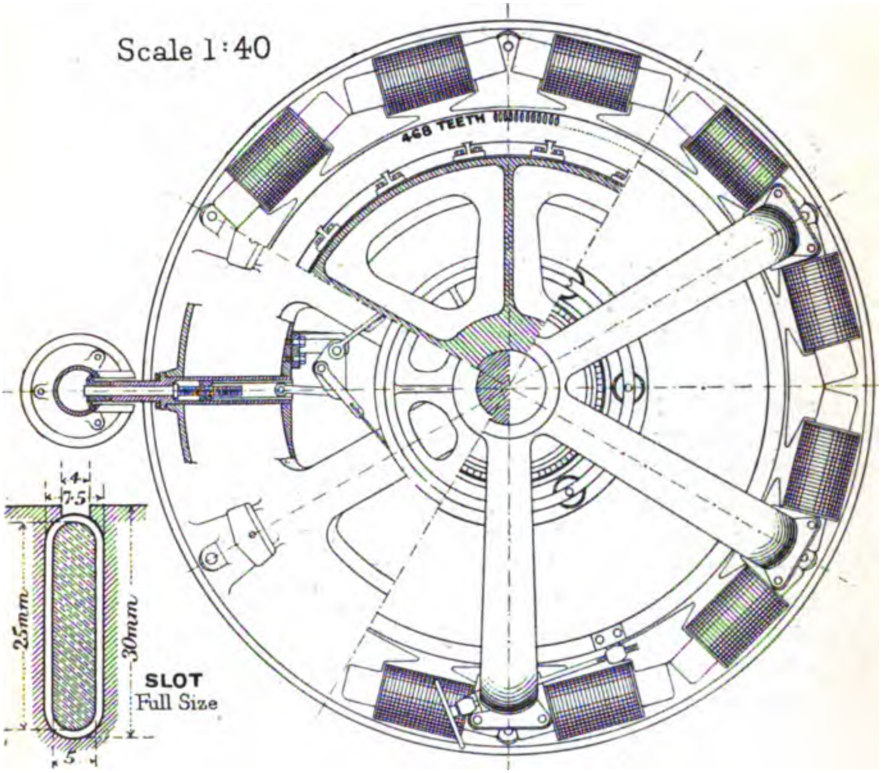


FIG. 454.—THURY'S ELECTROLYTIC GENERATOR: PLAN.

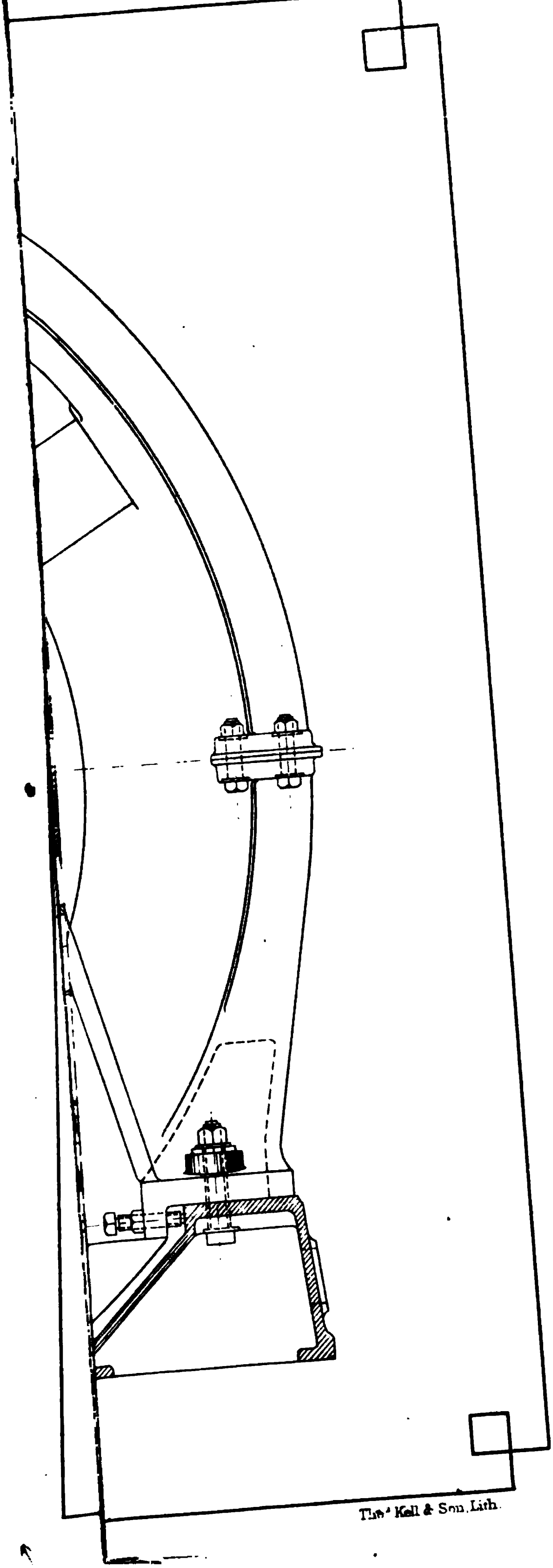
This machine, which is at work at Chèvres, is of the vertical type, and is driven by a 1200 horse-power turbine at a speed varying from 90 to 120 revolutions per minute. The output is 4000 amperes at 208 volts. This generator has the yoke and pole-pieces of the pattern peculiar to the designs of M. Thury. Each shunt-bobbin is wound with 448 turns of wire of 33 sq. mm. section, and the 12 coils are connected as usual in series. The armature has 468 slots, each slot containing one conductor of 120 sq. mm. section; the end connections being made by butterfly connectors of 140 sq. mm. section.

The commutator is 1000 millimetres in diameter, has 234 segments, with two working lengths of 390 millimetres, a steel ring being shrunk on the outside surface of the commutator at its middle point, to guard against any excessive centrifugal strain on the heavy commutator segments; this ring is, of course, adequately insulated from the surface of the commutator. The 4000 ampere current is collected by twelve sets of brushes, each set consisting of 24 carbon brushes, the 24 brushes being again subdivided into two sets of twelve brushes.

Thury Electrolytic Generator, MP 12—350—250, Fig. 455. This is one of Thury's large electrolytic machines designed for an output of 5000 amperes at 70 volts.

This generator is driven by a turbine on a horizontal shaft running at 250 revolutions per minute. It has twelve tangent poles, of the well-known Thury pattern, of soft iron with polar projections or pole-pieces of cast-steel; each shunt bobbin has about 200 turns of wire of 28 sq. mm. section, and the twelve coils in series have a total resistance of 1·2 ohms. There are two commutators, each delivering 2500 amperes at 70 volts; the two commutators are always connected in parallel, thus giving a combined output of 5000 amperes. A slotted ring winding is employed with two independent windings in the armature, each of these windings comprising 228 conductors, one conducter per slot, there being thus altogether 456 slots; the conductors have a cross-sectional area of 67 sq. mm. The commutators are 750 mm. in diameter, each having 228 segments, the useful length of the segments being 480 mm. There are twelve sets of brushes for each commutator with 15 carbon brushes per set.

An electrolytic generator by Kolben is shown in Plate XXII.; it is an MPC 18—400—100, and at full-load the output is 3500 amperes at 110 to 115 volts.



Thoˢ Kell & Son, Lith.

The poles are cast with the yoke, the material being cast-steel, the magnet-cores are circular, and cast-steel pole-pieces are screwed on after the field-spools have been placed in position. The field-spools have each 205 turns of wire 0·31″ in diameter bare, the full-load exciting current varying from 73·4 to 77 amperes, according as the machine is working at

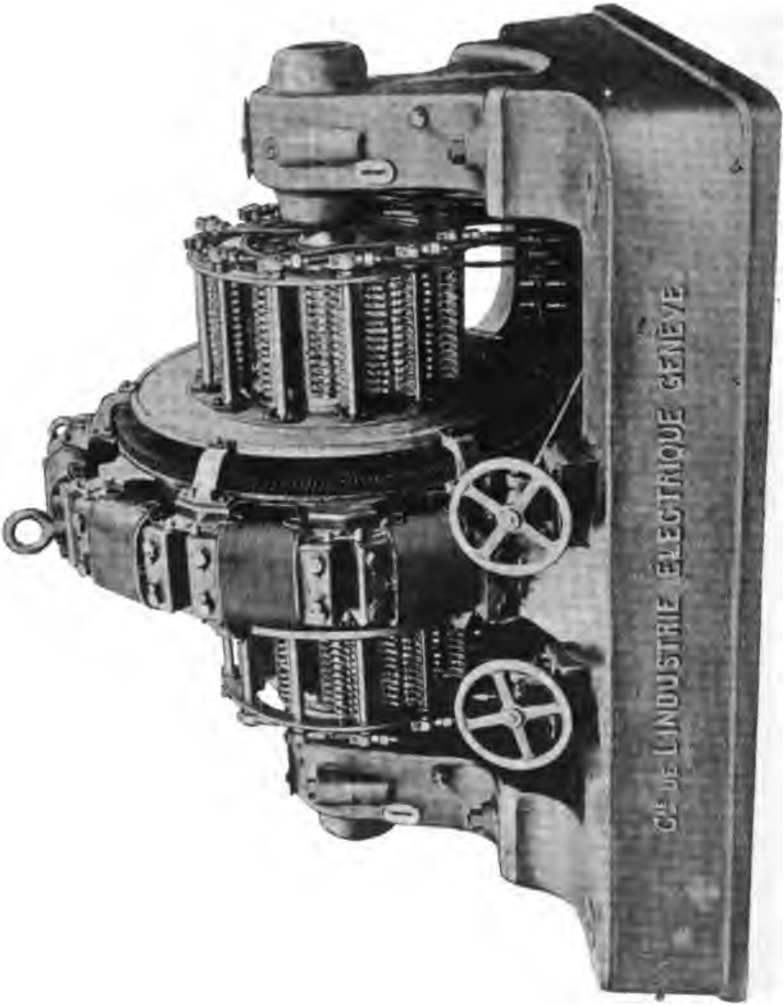


FIG. 455.—THURY'S ELECTROLYTIC GENERATOR, MP 12—350-250—70V—5000A.

110 or 115 volts. Thus about 8½ kilowatts are used in excitation or about 2¼ per cent. of the full output. The mechanical construction throughout is practically identical with that of the 10-pole Kolben machine described on p. 671 except as regards dimensions. There are 486 slots in the armature: in each slot lie two conductors of 0·093 square inch in section; each conductor having to carry about 194 amperes, the current density thus working out to about 2085 amperes per square inch of section.

Plate XXVI. illustrates a machine designed by Messrs. Alioth, of Basel, for electrolytic purposes, having a ring-winding sunk in slots, and two commutators, for collecting the current of 5000 amperes at 82 volts. This is MPC 12—410—250. The armature diameter in 62½ inches, the length between core-heads 15·8 inches. There are 312 slots, each 0·257 wide by 0·95 deep, and each containing one conductor of dimensions 0·158 thick, by 0·790 broad. The gap is 0·335 inch. The length of magnet-core is 9½ inches. Each commutator is 47·5 inches in diameter, and of 20 inches working length: each has 156 segments. The face-breadth of each segment is 0·48 inch, and the mica interposed is 33 mils thick. The two windings are independent of one another.

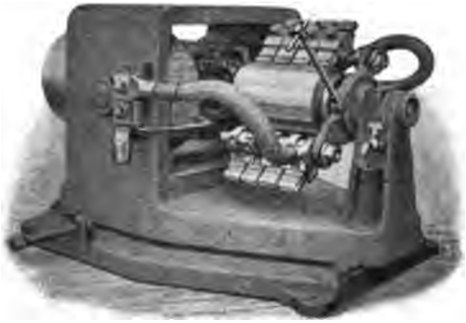
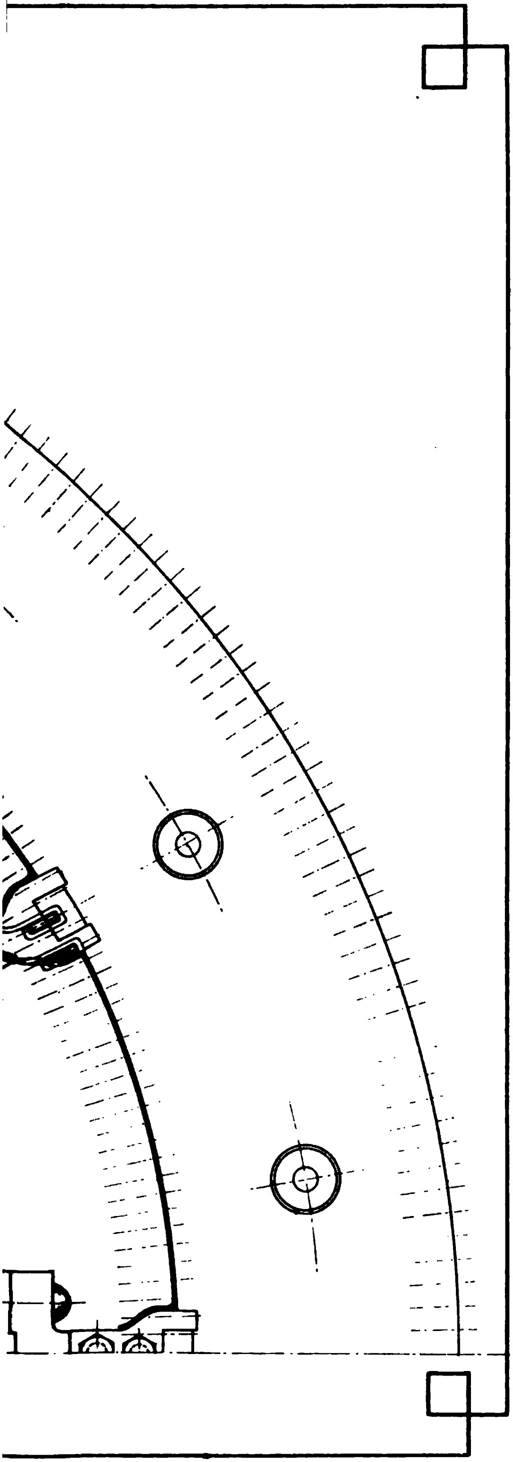


FIG. 456.—EDDY ELECTROPLATING DYNAMO: 2 KW.

The Eddy Manufacturing Co., of Hartford, Connecticut, has for twenty years turned out excellent small machines for

Plate XXVI



Thoˢ Kell & Son, Lith

electroplating. Fig. 456 depicts one of these, as now manufactured by the General Electric Co., to furnish 300 amperes at 5 volts.

With small machines the commutator is disproportionately large. Hence, to reduce cost, Mr. E. K. Scott recommends for electroplating the interior-pole type of machine (p. 687) in which the armature bars themselves serve as commutators.

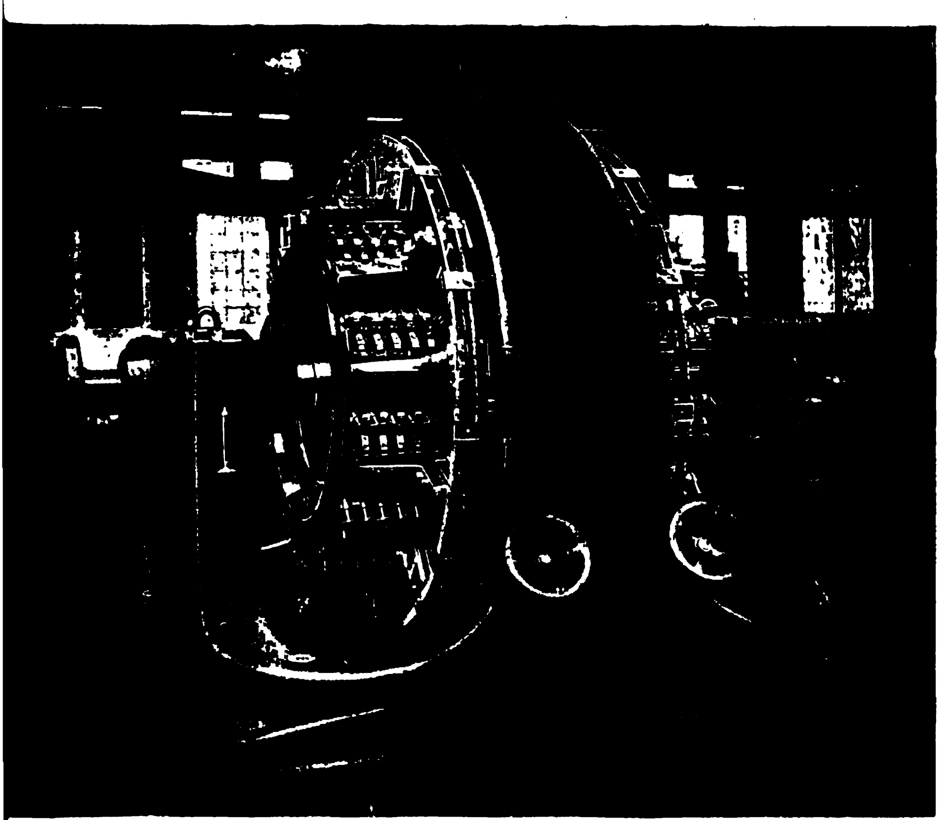


FIG. 457.—WESTINGHOUSE GENERATOR, MPC 12—360—250, FOR COPPER-REFINING.

Figs. 457 and 458 depict a Westinghouse machine of 360 kilowatts for copper-refining. It gives 4000 amperes at 90 volts, running at 250 revolutions per minute. It stands about 100 inches high, and is about 120 inches in length. It has two commutators to enable the large current to be collected.

A two-commutator machine MPC 8—12—450—4_v—3000_A constructed by the Holtzer-Cabot Co., of Boston, for copper-refining in Mexico, is described in the *Electrical World*, xxxviii. p. 479, Sept. 21, 1901.

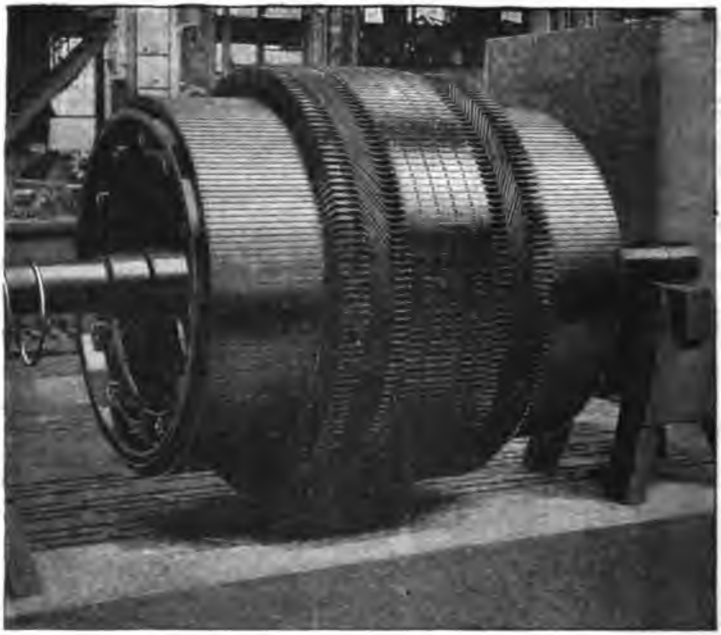


FIG. 458.—ARMATURE OF WESTINGHOUSE GENERATOR.

A steam turbine-driven generator for the electrolytic manufacture of caustic soda, constructed by Messrs C. A. Parsons & Co., of Newcastle, was described in *Engineering*, Oct. 16th, 1896.

DYNAMOS FOR ACCUMULATOR-CHARGING.

In central-station work where batteries of accumulators are used, the usual practice is to employ shunt dynamos capable of giving 25 or 30 per cent. higher electromotive-force than that at which the battery is to discharge; and their circuits are usually arranged so that the mains can be supplied, according to demand, either from the dynamos and accumulators together in parallel at the time of maximum load or from either separately. See Chapter XXIV. on *Boosters.*

Whenever dynamos are wanted for the sole purpose of charging accumulators, it is better to design them specially so that their magnets are not too highly saturated under working conditions. For then, during charging, when the counter electromotive-force of the cells gradually rises, the voltage of the dynamo also rises automatically, instead of remaining nearly constant as it would do if the magnetism were incapable of further rise. The result is that the charging current remains more nearly constant without intervention of an attendant.

APPENDIX TO CHAPTER XXI.

NUMERICAL STATISTICS ON ELECTRO-METALLURGY.

The following data are useful for reference in deciding what the electrical capacity of a dynamo must be in order that it may deposit metal in any desired quantity:—

Copper.

Current	1	ampere	deposits	0·000326	grammes	per second.
„	1	„	„	0·01957	„	per minute.
„	1	„	„	1·1739	„	per hour.
„	851·8	„	„	1	kilogramme	per hour.
„	386·4	„	„	1	pound	per hour.

To deposit 100 lb. of copper in a working day of 10 hours will require 3864 amperes of current flowing all the time; or, if conducted in ten baths in series with one another, will require 386·4 amperes, but in that case the dynamo will require to be of an electromotive-force ten times as great as for one single large bath. If electrolysis of the crude copper solution is carried on with carbon anodes, there will be required about 1·2 volts for each bath in series, or, at most, 15 volts for the ten baths.

Silver.

Current of	1	ampere	deposits	4·025	grammes	per hour.
„	112·7	„	„	1	pound	per hour.

Gold.

Current of	1	ampere	deposits	2·441	grammes	per hour.
„	185·8	„	„	1	pound	per hour.

Nickel.

Current of	1	ampere	deposits	1·099	grammes	per hour.
„	412·8	„	„	1	pound	per hour.

The following statistics as to the various pressures and currents required in various processes of electro-deposition are useful for reference :—

PRESSURE AT TERMINALS REQUIRED FOR DIFFERENT KINDS OF BATHS.

	Volts.
Copper (acid baths)	0·5 to 1·5
„ (cyanide bath)	3 „ 5
Silver	0·5 „ 1
Gold	0·5 „ 4
Brass	3 „ 5
Iron (steel-facing)	1 „ 1·3
Nickel on iron, steel, copper, with nickel anode, strike deposit with 5 volts, diminishing to	1·5 „ 2
Nickel on iron, steel, copper, with carbon anode	2 „ 4
Nickel on zinc	4 „ 7
Platinum	5 „ 6

CURRENT-DENSITY FOR PROPER DEPOSIT.

	Amperes per 100 sq. in.
Copper Typing—	
Best quality tough deposit	1·5 to 4
Good and tough (for clichés)	4 „ 10
Good solid deposit	10 „ 25
Solid deposit, sandy at edges	25 „ 40
Sandy and granular deposit	50 „ 100
Copper (cyanide bath)	2 „ 3
Zinc (for refining)	2 „ 3
Silver	1 „ 3
Gold	0·5 „ 1
Brass	3 „ 3·5
Iron (steel-facing)	0·5 „ 1·5
Nickel at first deposit 9 to 10 amperes per 100 square inches, diminishing afterwards to	1 „ 2

CHAPTER XXII.

ARC-LIGHTING DYNAMOS, AND RECTIFIERS.

IN cases where lighting is to be done exclusively by arc lamps in great numbers, it is usual to arrange the lamps all *in series*, even to as many as 100 to 200 lights, and to provide a dynamo-machine which will give a constant, or nearly constant, current at a sufficiently high voltage. The usual current for which arc lamps are designed is 10 amperes. Some lamps are designed, however, for 8 or 6 amperes, and some for 4 amperes. These are therefore exceptions. On the other hand, the arc lamps used for search-lights and lighthouse work are designed to take larger currents, up to 200 amperes or more. With continuous-currents arcs cannot be maintained burning steadily unless they are fed at a pressure of about 40 to 45 volts for each lamp. If the pressure is insufficient, the arcs will be unstable and give out a hissing sound. The steady arc behaves as though it exercised a counter electromotive-force of about 39 volts. When arc lamps are to be used *in parallel* with one another, the mains must have a greater difference of potential than 45 volts—55 or 60 volts is preferable—in order that additional resistances may be introduced to steady the currents through each lamp. Such additional resistances are not necessary when a number of arc lamps are used *in series*, as they help to steady one another. The great advantage in the series arrangement is the saving in copper thereby effected. Alternate-current arcs only need a pressure of 30 to 33 virtual volts.

In arc-lighting in series, the function of the dynamo is to keep the amperes constant, no matter how many or few lamps are in circuit; whilst each lamp is provided with a shunt device which governs the movement of the carbons, so that the feeding of them shall keep the length of the arc, and the volts at the terminals of the lamps, approximately constant.

We may take it, therefore, that a system of 20 arcs in series will require a dynamo giving a current of, say, 10 amperes, and a pressure, when all the lamps are in use, of nearly 1000 volts. This allows 45 volts per lamp, and 5 volts more for driving the current through the resistance of the wires between each lamp and the next.

It was suggested by Deprez in 1881, that by a species of compound winding, consisting of an initial excitation and a shunt excitation combined, a dynamo might be constructed to give a constant current at constant speed. The assumption which underlay his reasoning, that the magnetism is proportional to the exciting power, is, we know, not justified except for the early and unstable stage of magnetization; all attempts to produce a practical compound winding for this purpose have therefore failed.

For the production of constant currents at such high voltages as 2000 to 3000 volts the ordinary ring and drum armatures, wound in a closed coil, in numerous sections, and provided with a commutator consisting of numerous closely-packed parallel bars, have not been found entirely satisfactory, for the commutator of this type is liable to give way under the high pressure, and to deteriorate under the action of long sparks flashing over its surface from brush to brush under the wide alterations of lead that are inseparable with this mode of working. Nevertheless, good results have been obtained by several firms (see p. 752) in the use of high voltages in machines having ordinary commutators with many segments. Experience, however, is in the main against the use of armatures of this type. More simple forms are needed that will not break down under the conditions of work. These forms are usually associated with other modes of construction in which the armature winding does not constitute a closed coil.

OPEN-COIL DYNAMOS.

As explained on p. 53, it is possible to construct armatures in which the separate coils or sections of the windings are not united together in one closed circuit. An example is given in Fig. 459. This diagram (which should be compared with Fig. 26, p. 50) shows an armature consisting of two separate loops, set in planes at right angles to one another, so that when one is passing through the inactive region the other is in the position of maximum action. There is no reason why these two loops should not have each a separate 2-part commutator like that of Fig. 26; and one pair of brushes might press on both commutators. It is, however, obviously more convenient to unite these two commutators into a single one of four parts, as in Fig. 459; and then it will at once be seen that as this rotates between its pair of brushes one loop only will be in action at once, the other loop being cut out of circuit for the time being. It would clearly be possible to arrange any number of loops or coils in this way so that only that loop or coil which was passing through the position of maximum action should be feeding the brushes, all the rest being meantime open-circuited. A ring armature wound in sections might of course be similarly arranged, so that the pairs of sections have each a separate

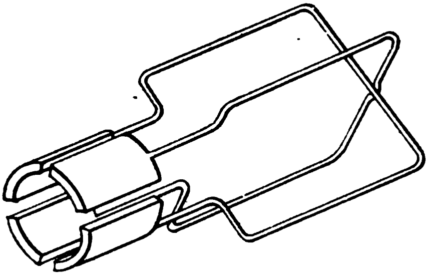


FIG. 459.
SIMPLE OPEN-COIL ARMATURE.

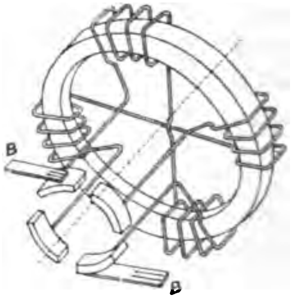


FIG. 460.—FOUR-PART OPEN-COIL RING ARMATURE.

commutator; and Fig. 460 (which should be compared with Fig. 33, p. 51) shows such a ring, but with the two commutators cut down and formed into a 4-part collector.

It will be noticed that each coil is joined at the back to the one diametrically opposite to it, and that the front ends of the coils pass to the commutator. As a matter of fact, it would make no difference in either of these armatures were the wires which cross at the back all united where they meet.

It will be seen that the position of the brushes with respect to the position of maximum action will not be the same as in the case of a closed-coil winding. In a closed-coil winding the diameter of commutation is near the coils of minimum action.

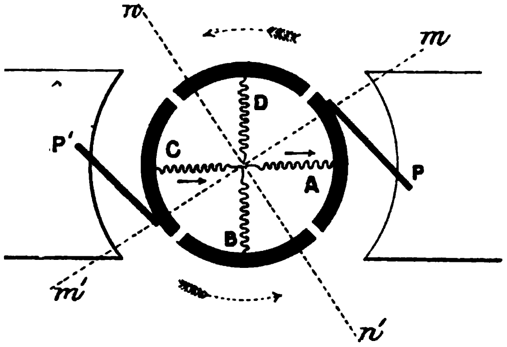


FIG. 461.—DIAGRAM OF OPEN-COIL ARMATURE.

With open-coil armatures the current is led directly from the coils of maximum activity.

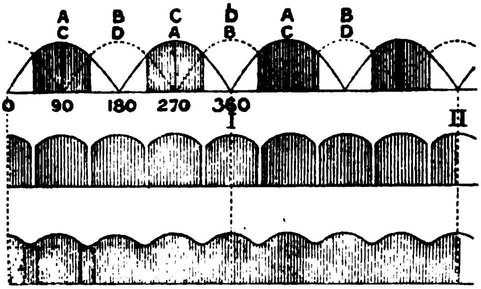
The current might be simultaneously collected from more than one coil at once, either (1) by making the pieces of the commutators overlap, or (2) by connecting to the brushes that touch on the line of maximum activity, another pair having either a forward or a backward lead. If we now consider Fig. 461 we shall see this a little more clearly. This figure is a diagram of such an armature, the coils or loops being here represented merely by wavy lines.

The wavy line A C may represent either a pair of coils such as there are in Fig. 460 on the ring, or may represent a single loop or group of windings round a drum. There is a pair of commutator-plates for A C, and another at right angles for B D. Coils A and C are just coming into the position of best action shown by the line *m m'*; they are delivering a current to the brushes P P', and this current will accordingly increase a little, and then decrease again. Meantime coils B and D are idle. If the four parts of the compound commutator each occupy just a quarter of the circumference, it is clear that when A comes into action its plane makes an angle of 45° with *m m'*, and that just as it leaves contact with the brush it makes again an angle of 45° on the other side, being in contact in all intermediate positions; and so with each coil as it passes the brushes. There will be a momentary break of current and a spark as the two successive segments pass under the brush, unless the brush touches both at once. Remembering that Fig. 31, p. 51, represents the alternating electromotive-force from a single loop or pair of coils, and that Fig. 32 represents the same electromotive-force rectified by the use of a simple 2-part commutator, we shall be able to represent the effect of our new arrangement by some such diagram as Fig. 462. The angles marked below are reckoned from the neutral line *n n'*. When coil A has gone round 90° from this position, it is in the position of maximum induction: but because segment A of the commutator is itself 90° in breadth, the current will be collected from 45° to 135°. The shaded portions of the curve show the discontinuous effect due to the coils A and C coming into circuit during two quarters of the rotation. The coils B and D come in in the intervals as indicated by the dotted lines. The induced currents will therefore present an approximate continuity depending on the arrangements of the commutator and the brushes. Fig. 463 represents the effect if there were gaps between the segments and the commutator; and it will be noticed that the electromotive-forces, though all of the same sign, are discontinuous. If the brushes thus left contact with one segment of the commutator before the next come into contact there would inevitably be a considerable amount of sparking, since the circuit would be entirely broken at such times. Fig. 464 shows the result of making contact with one set before the other set is cut out; the induced electromotive-force being now continuous, but with undulating fluctuations of strength. During the time when both sets of coils are in contact with the brushes, they are, of course, in parallel with one another. During this stage of the action the resistance of the armature is half as great as when one of the coils is cut out; but it is necessary to cut out the idle coil, otherwise some of the current from the active coil would flow back uselessly through the idle coil that was in parallel with it. During the time when the two sets of coils are in parallel they are not equally active. The induced electromotive-force is increasing in one and diminishing in the other; there is but a moment when they are equally active —when they make equal angles with $m\,m'$. At all other moments the higher electromotive-force of the more active coil tends to send a back-current through the less active coil. This is to a certain extent opposed by the self-induction of the less active coil, and if contact is broken just at the moment when the higher electromotive-force has reduced the current in the less active coil to zero, the commutation will be sparkless.

FIG. 462.

FIG. 463.

FIG. 464.



CURVES ILLUSTRATING THE PRODUCTION OF CURRENTS BY USING AN OPEN-COIL 4-PART ARMATURE.

From what has now been said, it will be clear that open-coil armatures may be constructed either as rings, drums, or disks. They may be arranged to run either in a bipolar or

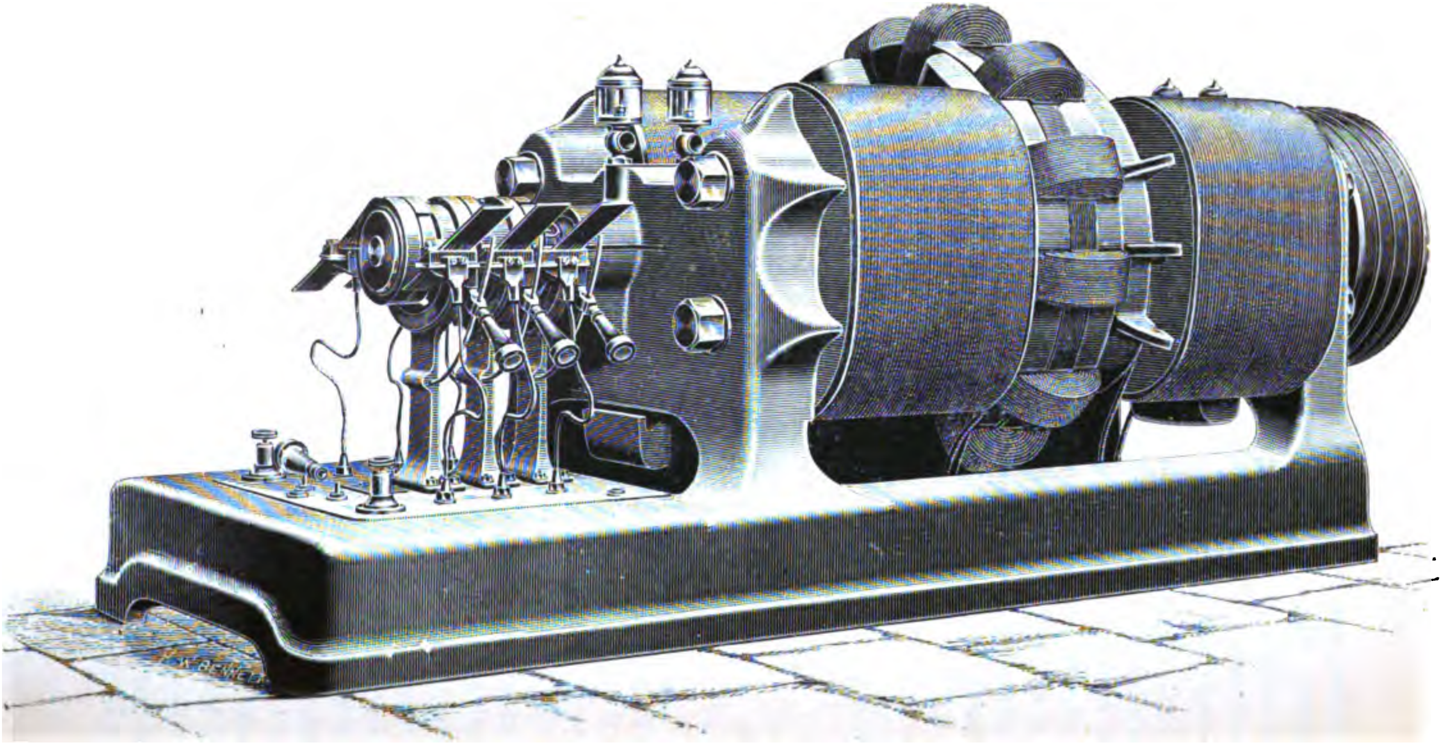


FIG. 465.—BRUSH ARC-LIGHT DYNAMO.

in a multipolar magnetic field. The principal dynamos constructed upon this plan are the Brush machine and the Thomson-Houston machine ; but there are a few others which also come within the category of open-coil dynamos.

Brush's Dynamos.—One of the best known of these machines is the Brush dynamo (Fig. 465). The magnet heads are insulated with sheets of vulcanized fibre, thoroughly varnished. The cores are, however, first surrounded with a thin sheet of copper, soldered together at the edges so as to form a continuous tube or envelope. The object of this copper coating is to deaden or damp out sudden variations of magnetism of the iron cores. Over the copper envelopes are wound four or five thicknesses of very heavy paper saturated with shellac varnish to insulate the wire from the iron. In some of the Brush dynamos there is a double winding, a shunt or "teazer" circuit being added to maintain the magnetism of the field-magnets when the main circuit is opened. An automatic regulator, consisting of a carbon rheostat connected as a shunt to the magnet winding and operated by a solenoid in the main circuit, is applied to keep the current constant (see Chapter XXVI.).

The armature has, like the Pacinotti ring, projecting teeth between the coils, but, unlike that early form of armature, the successive sections are not connected in a closed circuit.

The ring is built up of a thin iron ribbon 1·5 millimetres thick. Fig. 466 shows its construction, though in reality a larger number of pieces of thinner iron than is shown are used. The ribbon is wound upon a circular foundation ring A′, projecting cross-pieces of the same thickness (marked H) being inserted at intervals to separate the convolutions, admit of ventilation, and form suitable projections between which to wind the coils. It is secured by well-insulated radial bolts. All iron parts which are to adjoin the wire of the "bobbins" are covered first with a layer of strong heavy canvas saturated with shellac varnish, and in the case of the armatures of the larger machines there are additional layers of tough paper saturated with shellac varnish. A sheet of strong cotton cloth inserted occasionally separates contiguous layers of wire from each other both in the armature bobbins and in the coils of the field-magnets. All the bobbins are wound by hand, in the same direction, and the inner ends of diametrically opposite bobbins are soldered together, and carefully insulated from all other wires and adjacent metal. The free outer ends of each pair of bobbins are separately carried through a boring in the shaft, and connected to diametrically opposite segments of the commutator.

For each pair of coils there is a separate commutator. In the No. 8 L size of machine, which is depicted in Fig. 465, there are 12 coils on the armature, six commutators grouped in three pairs, and three sets of brushes. This size is commonly known as a "60-light" machine. Its electromotive force at a speed of 800 revolutions per minute is 3000 volts.

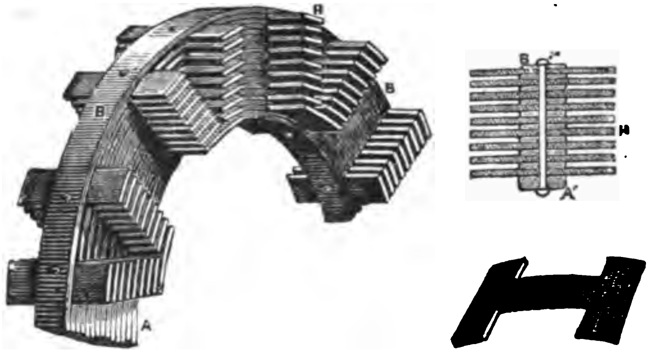


Fig. 466.—Core of Brush Ring.

In considering the method in which the coils are joined up to the commutator, we will take the case of an 8-coil armature with the commutators grouped in two pairs; it will then be easy to extend the method to the case of a twelve-coil machine.

Continuity is obtained in the currents by making the two parts of the commutator of each pair of coils overlap those of the commutator belonging to the pair of coils that is at right angles, one pair of brushes resting on both commutators

Fig. 467 is a diagram illustrating this device. Each pair of segments overlaps the other to the extent of 45°. Each of the two pairs of coils is thus cut out twice during a revolution; it is twice in circuit alone, as when the brushes are at AA, and four times in circuit along with the pair that is at right angles, when the brushes are at B B′. Fig. 468 shows in perspective the commutator of an 8-coil Brush armature.

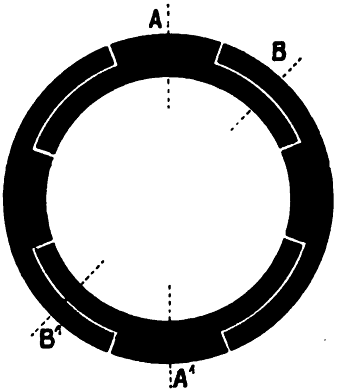


FIG. 467.—PAIR OF OVERLAPPING COMMUTATORS.

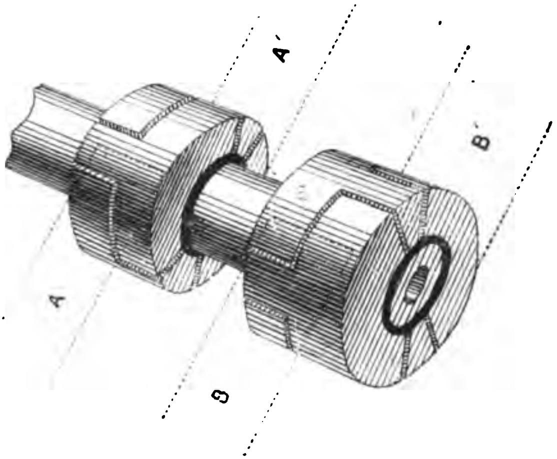


FIG. 468.—BRUSH COMMUTATOR FOR ARMATURE WOUND WITH FOUR PAIRS OF COILS.

There are really four commutators here, corresponding to the four pairs of coils, grouped in pairs; one pair of commutators being set one-eighth of a rotation (45°) in advance of the other. It will be seen from this figure that while the brushes A A (shown in dotted lines) are receiving current from *one pair* of coils only, the brushes B B′ are at the same instant receiving the current from *two pairs* of coils which are joined in parallel with one another in consequence of both of their commutators touching the same pair of brushes. The arrangement may be still further studied by the aid of Fig. 469, which also illustrates the way of connecting the brushes with the circuit. In this figure the eight coils are numbered as four pairs, and each pair has its own commutator, to which pass the outer ends of the wire of each coil, the inner ends of the two coils being united across to each other (not shown in the diagram). In the actual machine, each pair of coils, as it passes through the position of least action (i. e. a position somewhat past the vertical dotted line midway between the poles (Fig. 469) and when the number of magnetic lines passing through it is a *maximum*, and the rate of change of these magnetic lines a *minimum*) is cut out of connexion. This is accomplished

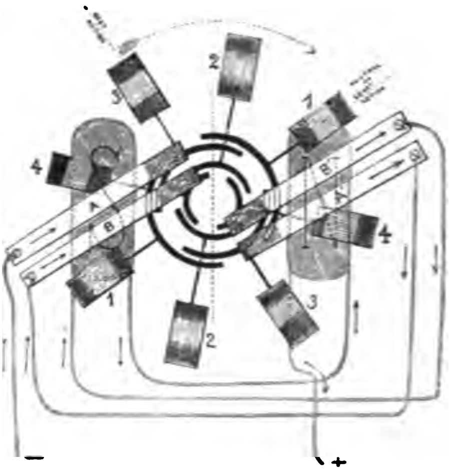


FIG. 469.—CONNEXIONS OF BRUSH DYNAMO.

by causing the two halves of the commutator to be separated from one another by about one-eighth of the circumference at each side. In the figure it will be seen that the coils marked 1, 1, are "cut out." Neither of the two halves of the commutator touches the brushes. In this position, however, the coils 3, 3, at right angles to 1, 1, are in the position of best action, and the current powerfully induced in them flows through them from the brush marked A (which is, therefore, the negative brush) to that marked A′. This brush is connected across to the brush marked B, where the current re-enters the armature. Now, the coils 2, 2 have just left the position of best action, and the coils 4, 4 are beginning to approach that position. In both these pairs of coils, therefore, there will be a rather weaker electromotive-force. The current on passing into B splits, part going through coils 2, 2, and part through 4, 4, reuniting at the brush B′, whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A.

Thus the coils in which there is a maximum electromotive-force are joined in series with coils in which the electromotive-force is weaker, though by a method different from that employed in a closed winding armature. As the armature rotates, coils 4, 4 come to the position of maximum electromotive-force, and they are then in series with coils 1, 1 and 3, 3, so that the electromotive-force of the machine varies very little with the change of the position of the coils. In some machines it is arranged that the current shall go round the field-magnets, after leaving brush A′, and before entering brush B.

The following table summarises the successive order of connexions during a half-revolution :—

First position. (Coils 1, 1 cut out.)

$$A - 3 - A' ;\ \begin{tikzcd}[row sep=tiny, column sep=small] & 4 \arrow[dr, dash] & \\ B \arrow[ur, dash] \arrow[dr, dash] & & B' \\ & 2 \arrow[ur, dash] & \end{tikzcd} ;\ \text{Field-magnets} - \text{External circuit} - A.$$

Second position. (Coils 2, 2 cut out.)

$$\begin{tikzcd}[row sep=tiny, column sep=small] & 1 \arrow[dr, dash] & \\ A \arrow[ur, dash] \arrow[dr, dash] & & A' \\ & 3 \arrow[ur, dash] & \end{tikzcd} ;\ B - 4 - B' ;\ \text{Field-magnets} - \text{External circuit} - A.$$

Third position. (Coils 3, 3 cut out.)

$A - 1 - A'$; $B \overset{2}{\underset{4}{\Diamond}} B'$; Field-magnets – External circuit – A.

Fourth position. (Coils 4, 4 cut out.)

$A \overset{3}{\underset{1}{\Diamond}} A'$; $B - 2 - B'$; Field-magnets – External circuit – A.

By rocking the brushes forward, a point can be found at which the sparking is reduced to a minimum.

From the foregoing considerations, it will be clear that the four pairs of coils in the Brush machine really constitute four separate machines, each delivering alternate currents to a commutator, which commutes them to intermittent unidirectional currents in the brushes; and that these independent machines are ingeniously united in pairs by the device of letting one pair of brushes press against the commutators of two pairs of coils. Further, that these paired machines are then connected in series, by bringing a connexion round from brush A′ to brush B.

In the 12-coil machine (Fig. 466) there are three pairs of commutators; the segments of each pair are joined to four coils at right angles to each other, and the pairs are mounted on the shaft so that the first pair joined to coils 1, 4, 7 and 10 has a lead of 30° in advance of the second pair joined to coils 2, 5, 8 and 11, and the third pair joined to coils 3, 6, 9 and 12 has a lag of 30° behind the second pair. The way the brushes are connected up in series is shown in Fig. 470.

Multipolar Brush machines are now made to be driven direct from the engine shaft. At the station of the Mutual Electric Light and Power Co., Chicago, there are three machines driven direct by Willans engines at 500 revolutions per minute. Each machine is capable of lighting 125 arc lamps in series. The automatic regulator regulates so closely that any number of these lamps may be thrown off and on with impunity. The armature of these machines is 39 inches in diameter and has 24 coils, that is six sets of four coils each. All the coils in any one set are in the same position relatively to the four poles, and are joined in series just as two coils are joined in series in a two-pole machine. The connexions to the commutators are on exactly the same principle as in the case of the 12-coil armature considered above, with this modification, that a difference of position of 45° on the armature corresponds to a difference of 90° in the 2-pole machine. Each of the three portions of the commutator, therefore, consists of eight sections, instead of four sections ; the sections that are diametrically opposite being interconnected.

An interesting example of a modern Brush arc-lighter is shown in Figs. 471 and 472. This machine has an output of 76·8 kw. at 500 revolutions per minute and serves to supply one hundred and sixty 2000 candle-power arc-lamps. The lamps are arranged in four separate circuits each of which is supplied from one of the four double commutators to be seen in the illustrations. Eight coils are connected to each of these double commutators, which are provided with eight segments. It will be seen that the eight coils form virtually two armatures of four coils each, the four coils being all in the same relative position in the field and being always connected in series. Each of the two four-coil armatures is successively put in parallel with its fellow, cut out of circuit, put in parallel, and put to work alone on the circuit when the cycle of operations recommences.

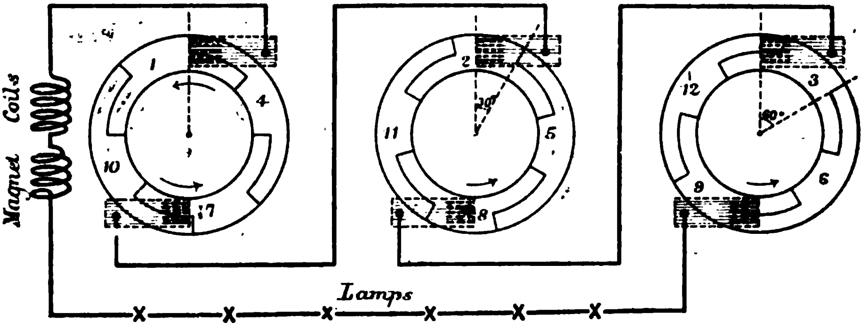


FIG. 470.—CONNEXIONS OF A 12-COIL BRUSH DYNAMO.

The illustrations show two rings for lubricating each bearing and the details of the thrust bearing at the commutator end which has six grooves. The automatic regulator is shown very clearly in Fig. 471.

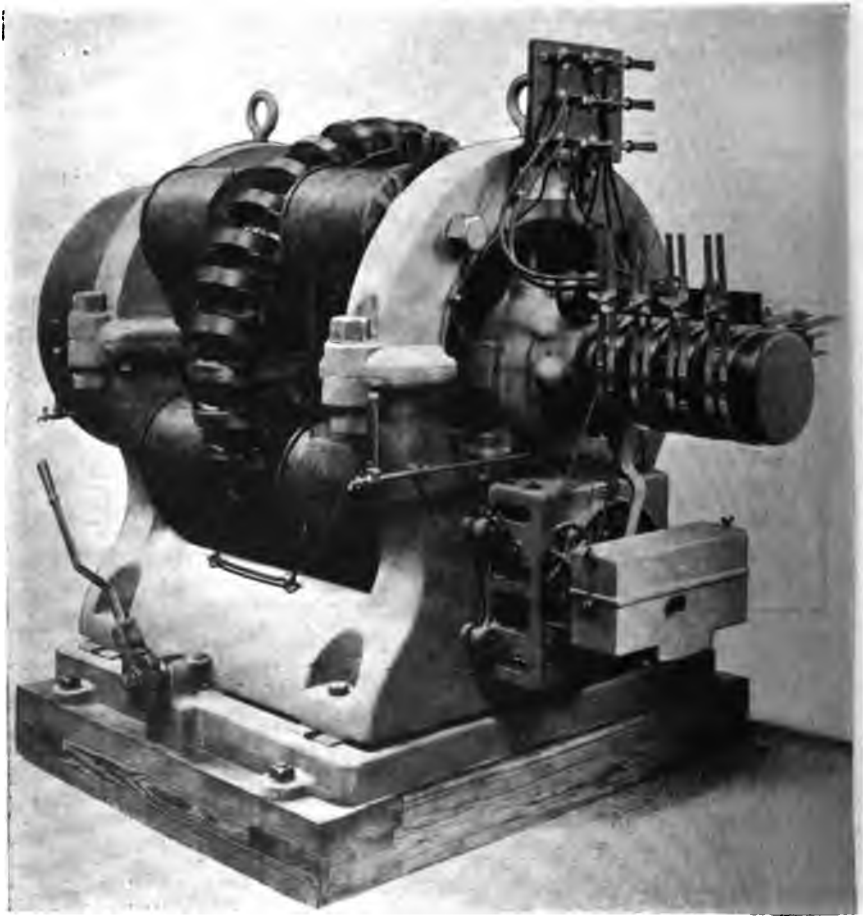


FIG. 471.—BRUSH 4-POLE ARC LIGHTER.

Some elaborate tests on Brush dynamos, with two different patterns of armature, were made[1] in 1889 by Mr. Murray of Melbourne. These show commercial efficiencies of about

---

[1] *Journal Inst. Electrical Engineers*, xvii. 710, Nov. 1889.

69·8 per cent. in machines with core-plates 0·05 inch thick, and of about 78 per cent. in those with core-plates 0·022 inch

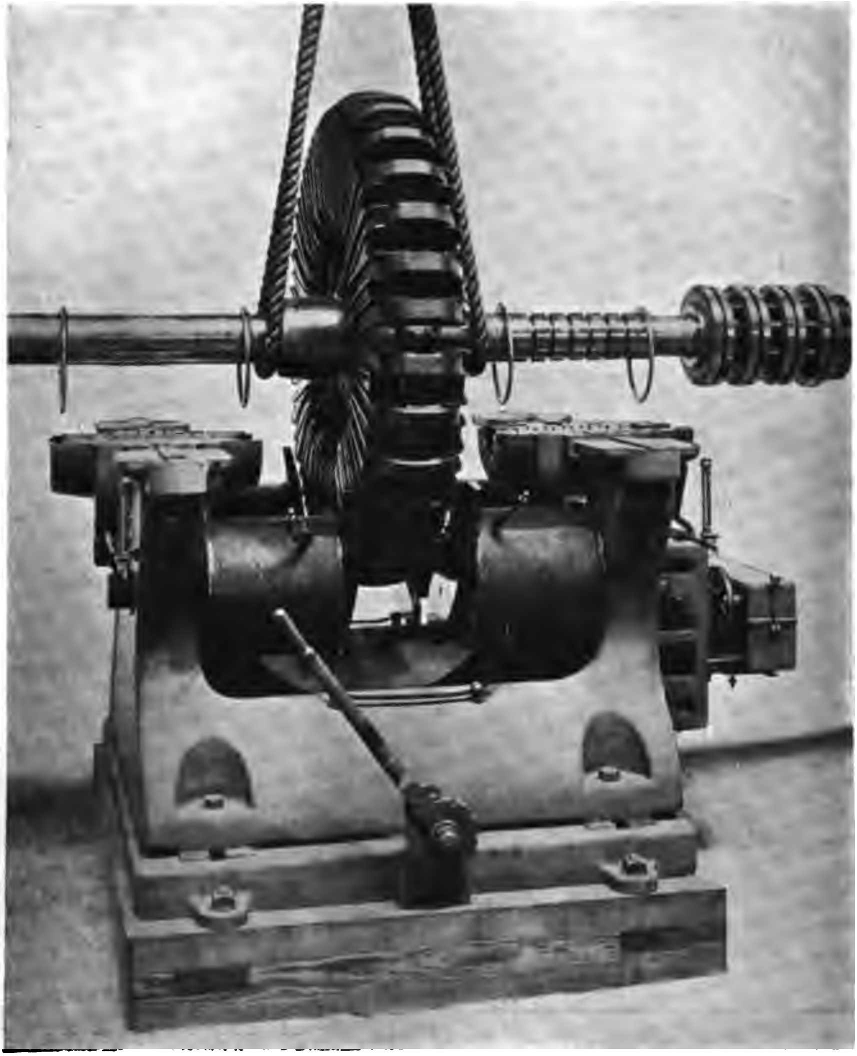


FIG. 472.—BRUSH 4-POLE ARC LIGHTER (TOP REMOVED).

thick. The values of B attained were about 4800 in field-magnet cores and 27,000 in the armature cores. The fluctuations of the current were about 1·5 per cent.

For further tests see Thurston in *Journal of Franklin Institute*, Oct. 1886. Consult also a small volume, ' Electrical Engineers' and Students' Chart and Handbook of the Brush Arc Light System,' by H. C. Reagan, jun. (New York, 1895).

Thomson-Houston Dynamo. — This machine, which is equally remarkable, was designed by Professors Elihu Thomson of Lynn and Edwin J. Houston of Philadelphia. It is unique in having a spherical armature with a 3-part commutator revolving between the cup-shaped poles of an introverted field-magnet. As will be seen from Fig. 473, the field-magnet core consists of two flanged iron tubes furnished at their inner ends with hollow cups cast in one with the tubes, and accurately turned to receive the armature. Upon the tubes are wound the coils C C′, and afterwards the two parts are united by means of a number of wrought-iron bars *b b*, which constitute the yoke of the magnet and at the same time protect the coils. The magnets are carried on a framework, which also supports the bearings for the armature shaft X. The original form of the armature, shown in Fig. 473, had a very remarkable winding. There were but three coils. The

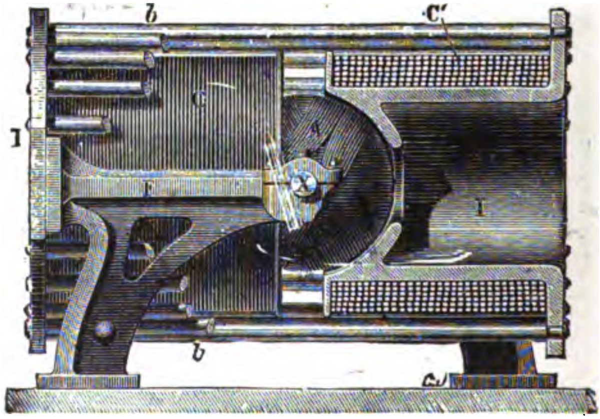


FIG. 473.—THOMSON-HOUSTON ARC-LIGHT DYNAMO.

inner ends of these were united together *and not connected to any other conductor.* The three wires were then wound over an iron shell in three sets of windings making 120° with one another, and arranged to be at equal average distances from the core, while their overlapping made the external form nearly spherical. The later ring armature, Fig. 474, has six groups of coils arranged in three pairs. The three pairs are themselves connected star-wise, having a common junction for three of their ends, the three other ends of the wires being brought down through the hollow shaft, and joined to the three segments of the commutator. The coils are replaceable singly.

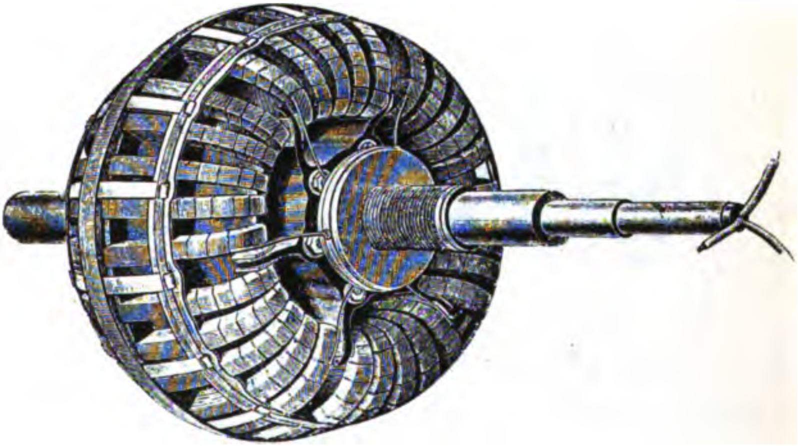


FIG. 474.—RING ARMATURE OF THOMSON-HOUSTON DYNAMO.

When this armature is rotated within the cavity between the cup-shaped poles alternate currents are generated in each coil in turn, and it now remains to consider how these alternate inductions are rectified and combined by the commutator. In the diagrams which follow, the rotation is represented as left-handed, as viewed from the commutator-end of the shaft as it is in practice. Fig. 475 represents the arrangement in diagram. The three coils represented diagramatically by the three lines A B C, are united at their inner extremities, each outer end being led to one segment of a 3-part commutator. There are two positive brushes P and F, and two negative brushes P′ and F′. The current delivered to P and F first flows round one of the field-magnets, thence goes to the outer circuit of lamps, returning through the other field-magnet to P′ and F′. In Fig. 475, in which the neutral line is at right angles to *m m*′, there will be an outward current in A and an inward one in C; B being for the moment cut out of circuit as it passes through the neutral position. Continuity is obtained by the device mentioned on p. 731, of having the second pair of brushes F F′ following the pair P P′. In this position of the armature A and C make about equal angles with the line of maximum action *m m*′, hence the two electromotive forces in these coils are for the moment about equal,

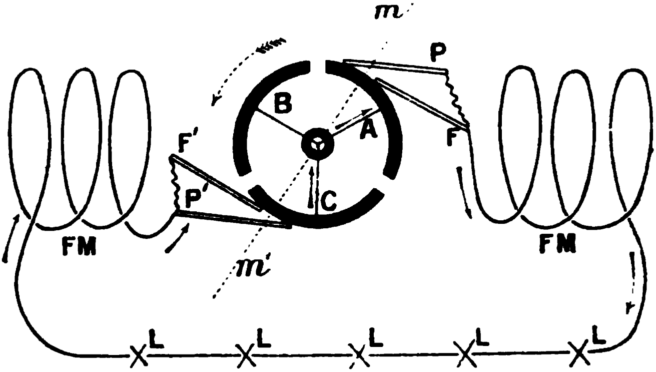


FIG. 475.—COMMUTATOR AND CIRCUIT OF THOMSON-HOUSTON DYNAMO.

but that in A is increasing, that in C decreasing. As these coils are now in series, their separate electromotive-forces are of course added together. A moment later A will be in the position of maximum induction; C will be rapidly approaching the neutral position and B will again begin to have electromotive-force induced in it. B and C will for the moment be in parallel with one another and in series with A. Then C comes to the neutral position and is cut out of circuit, while A and B are in series, and so forth.

If the width of the gaps between the segments of the commutator be equal to the width between the adjacent brushes, each coil will be out of circuit whenever it is more than 60° from the position of maximum action, and the time during which any two coils are in parallel will be practically nil. But if the brushes F F′ follow at a considerable angle—about 60° in practice — behind the brushes P P′, there will be considerable duration of the stage during which two coils are in parallel.

The regulation of this machine to maintain a constant current is accomplished by an automatic shifting of brushes. The actual method now used is termed "backward" regulation. The pair of "following" brushes F F′ is shifted backwards to *f f′* as shown in Fig. 476, whilst at the same time the leading brushes P P′ are shifted forward through an angle one-third as great towards *p p′*. If, as stated above, the brushes are 60° apart under normal conditions, there will be exactly 120° on either side between the positive brushes P F and the negative brushes P′ F′; and as 120° is the exact length of each segment of the commutator, no coil will be cut out, and parallelism will subsist between two coils through angles of 60°: that is to say, there will always be two of the three coils in parallel with one another and in series with the third coil. The six stages of change will be :—

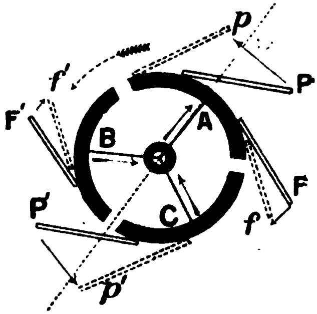


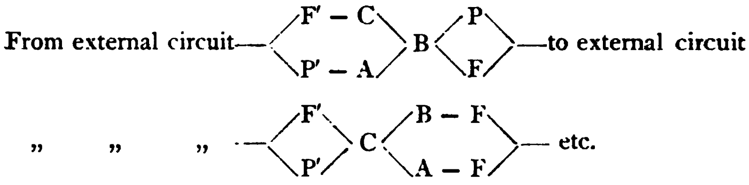
FIG. 476.—COMMUTATING POSITIONS.

$$\text{From external circuit}—\left\langle\begin{matrix}F'-B\\P'-C\end{matrix}\right\rangle A\left\langle\begin{matrix}P\\F\end{matrix}\right\rangle—\text{to external circuit.}$$

$$\text{” ” ”}\;—\left\langle\begin{matrix}F'\\P'\end{matrix}\right\rangle B\left\langle\begin{matrix}A-P\\C-F\end{matrix}\right\rangle—\;\text{” ” ”}$$

$$\text{” ” ”}\;—\left\langle\begin{matrix}F'-A\\P'-B\end{matrix}\right\rangle C\left\langle\begin{matrix}P\\F\end{matrix}\right\rangle—\;\text{” ” ”}$$

$$\text{” ” ”}\;—\left\langle\begin{matrix}F'\\P'\end{matrix}\right\rangle A\left\langle\begin{matrix}C-P\\B-F\end{matrix}\right\rangle—\;\text{” ” ”}$$



Now suppose the current to become too strong owing to reduction of number of lamps in circuit, the "following" brushes are made to recede. This will shorten the time during which any single coil in passing through the maximum position is throwing its whole electromotive-force into the circuit, and will hasten the moment when it is put in parallel with a comparatively idle coil. During such movements of regulation the whole machine is momentarily short-circuited six times during each revolution by F receding so far towards P′, and F′ receding so far towards P, as that both touch the same segment of the commutator at one instant. The action is assisted by the slight advance of P and P′, but the main object of this advance is to lessen the sparking. If the current is too weak, then the pairs of brushes must be made to close up, thereby reducing the time during which the most active coils are in parallel with those that are less active.

Regulating Gear.—This motion of advance and retreat is accomplished by the simple link-gear not shown in any of the figures. The automatic movement is imparted by the regulating electromagnet R (Fig. 477), whose pole, of paraboloidal form, attracts its armature according to the current flowing around it, and raises the arm A. The circuits which operate this mechanism are also shown. Normally the electromagnet R is short-circuited through a bye-pass circuit, and only acts when this circuit is opened. At some convenient point of the main circuit two solenoids are introduced, their cores being supported by a spring; and the yoke of the cores operates the contact lever S. If the current becomes too strong this contact is opened, and the regulating magnet R raises the arm A. During running the lever S is continually vibrating up and down, and so altering the brushes to the requirements of the circuit. A carbon shunt of high resistance *r* is added to minimise the destructive spark at S. It might be expected that with only three parts to the commutator, the sparks occurring as the segments pass under the brushes would speedily destroy the surface. This difficulty has been met by Professor Thomson in the boldest manner. By means of a small

mechanical blower, fixed upon the shaft behind the commutator, intermittent blasts of air are blown exactly at the right moment so as virtually to blow out the spark. The three segments of the commutator are separated by gaps ; and in front of each of the leading brushes there projects a nozzle which discharges a blast, alternately, three times in each revolution.

Advantages of Open-coil Dynamos.—The two great typical open-coil dynamos—those of Brush and of Thomson-Houston—appear to have certain qualities which render them specially applicable as constant-current dynamos for series arc-lighting. A considerable proportion of all the arc-lights in the world are run by one or other of these machines. It would seem that the closed-coil dynamos, whether of the ring or of the drum type, are not so well adapted for furnishing the very high electromotive-forces needed for this work. The commutator, with its many parallel bars insulated with mica (which is the indispensable adjunct of the closed-coil armature), rapidly deteriorates when exposed to the inevitable sparking and wide alterations of lead which are inseparable from the constant-current method of working. For this method of distribution of electric energy, nothing will stand wear and tear so well as the simple air-insulated commutators described in this chapter. As a partial set-off against these advantages may be reckoned the somewhat lower plant efficiency of open-coil machines.

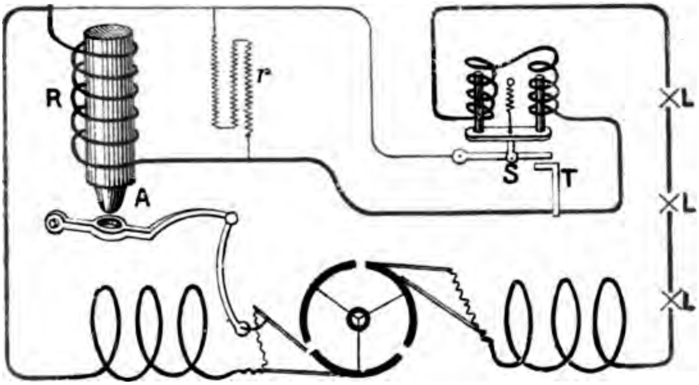


FIG. 477.—CIRCUITS OF THOMSON-HOUSTON SYSTEM.

Some tests of a closed-coil arc dynamo have been published by Owen and Skinner in the 'Proceedings of the American Inst. Electrical Engineers' for 1893.

A special study of the curves of induction in the armature of a Thomson-Houston arc-light machine has been made[1] by Mr. Milton F. Thompson, who found the total current at full-load to fluctuate between five and eight amperes, six times in each revolution; the mean current being 6·8. The fluctuations of electromotive-force in each individual coil were very remarkable; the curves being singularly irregular, falling to near zero twelve times in each revolution.

Westinghouse Arc-Lighter.—The Westinghouse arc-lighting machine resembles a two-phase alternator with revolving armature having coils of many turns sprung over large T-shaped teeth. The coils in each "phase" are in series, and each series is connected at its ends to a rectifying commutator. The field-magnets are separately excited at 125 volts. The 75-arc machine, running at 650 r.p.m., generates 9·5 amperes at 3750 volts. The high armature reaction renders any external regulator unnecessary.

OTHER ARC-LIGHT MACHINES.

Bradley's Dynamo.—Mr. C. S. Bradley has constructed a dynamo with a closed ring armature, in which the difficulty of commuting at high pressure is reduced by having four distinct commutators, the brushes of which are joined in series. A machine of somewhat similar type, designed by M. Hurmuzescu for testing purposes, was described in the last edition of this book.

Sperry's Dynamo.—An arc-light dynamo with a Gramme armature is that of Sperry, the distinguishing feature of which is the use of internal as well as external pole-pieces. It was illustrated in the previous edition of this book.

Wood's Dynamo. — This is also a modified Gramme machine.[1] To obviate sparking, there is an auxiliary brush placed 5 to 10 sections ahead of the collecting brush; and the voltage is varied by a device which shifts the brushes forward. The width between the auxiliary brush and that behind it is varied, being narrow where commutation has to occur in strong fields, and wide for weak fields, thus securing sparkless reversal in either case. One of the largest arc-lighting stations in the world, that at St. Louis, Missouri, is supplied with 53 of these dynamos, each capable of feeding 60 arc-lamps.

---

[1] *Electrical World*, xvii. 392, 1891, and *Electrical Review*, xxviii. 773, 1891.

For other makers of arc-light machines of the closed coil type, the reader is referred to previous editions of this book.

F. B. Crocker[2] has pointed out that it is desirable to use carbon brushes with high-voltage closed-coil dynamos, as copper wears off on the mica insulation, causing a thin film of copper which promotes sparking.

He has designed successful machines having as few as 108 parts in the commutator, capable of dealing with 11,000 volts.

Drooping Characteristics.—A method which, though not in itself securing constancy of current, is much followed in the construction of arc-lighting dynamos, should here be explained. Attention was drawn on p. 330 to the drooping form of the characteristics of certain series-wound machines. It is obvious that if this effect is sufficiently exaggerated, the drooping portion of the characteristic will correspond to the case of an approximately constant current. The drooping characteristic is important (see p. 346) in promoting the steady working of arc-lamps in series in the circuit.

The influences that tend to cause the characteristic of the series dynamo to turn down after reaching a maximum height are: (1) the demagnetizing effect of the armature current when there is a positive lead at the brushes; (2) the saturating of the iron of the armature core and that of the field-magnets; (3) the leakage of magnetic lines from the field-magnet; (4) the peculiar commuting arrangements in certain machines—for example, the open-coil dynamos mentioned previously—which make their effective electromotive-force vary greatly with the position given to the brushes; (5) high internal resistance, and self-induction. As the demagnetizing effect of the armature current is nearly proportional to the current and to the angle of lead, and as the angle of lead is itself nearly proportional to the armature current, it follows that the whole demagnetizing effect is nearly proportional to the square of the armature current. In Fig. 478, let the curve E_1 represent the electromotive-force (at a given speed) when the field-magnets are separately excited, the armature circuit being left open; this includes the effect of (2) and partially (3) above. On the same diagram a curve having ordinates proportional to C_a, and of such a magnitude as to represent the demagnetizing action of the armature current, may be plotted. Deducting the ordinates of this curve from those of curve E_1 we get curve E_2, the drooping characteristic. The trouble with all machines of this class is the sparking at the brushes consequent on the variability of the angle of lead.

---

[1] See *Electrical World*, xii. April 23, 1887, and xiv. 54 and 260, 1889; also xvii. 4, 1891. [2] Address before Electrical Congress, Chicago, Aug. 24, 1893.

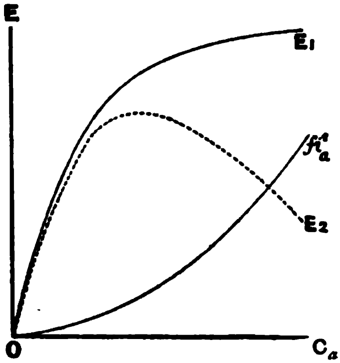


FIG 478.

The effect of a drooping characteristic can to some extent be obtained by inserting in the external circuit a resistance of from 1 to 2 ohms. And this is preferable to having an internal resistance that would add to the heating of the armature. But such auxiliary resistance should be coiled on an iron core, since self-induction here is of value in steadying the current.

Rectifiers.—The success of the open-coil dynamos has led inventors to devise machines known as *rectifiers*, to produce from an alternate-current supply currents suitable for series arc-lighting. Such machines consist of 3 parts (*i*) a special transformer yielding an alternating current of constant strength; (*ii*) a rotating rectifying commutator, consisting of a number of air-insulated segments, the odd numbers of which are joined together and to one end of the alternating circuit, the even numbers being also joined together and to the other end of the alternating circuit; (*iii*) a synchronous motor to drive the commutator. The commutator must have as many segments as the motor has poles. The best-known rectifier for arc-lighting is that of Ferranti, while that of Pollak has been successfully used for charging accumulators.

CHAPTER XXIII.

SPECIAL TYPES OF DYNAMOS.

IN this Chapter are considered the following special types of dynamos :—

a. Extra high voltage generators ;
b. Very high speed machines (Steam-turbine dynamos ;
c. Very low speed machines (Exciters) ;
d. Double-current generators ;
e. Three-wire generators, and multi-voltage generators ;
f. Homopolar (Unipolar) generators.

Extra High Voltage Generators.—For all continuous-current generators working at 1000 volts or over, the utmost attention must be given to the due insulation of every part.

For transmission of power to long distances by continuous currents, and for laboratory purposes, dynamos are occasionally required giving extra high pressure. Crocker[1] has constructed a machine yielding 0·3 of an ampere at 11,000 volts, the commutator consisting of 108 parts. A continuous-current dynamo[2] of exceptionally high voltage, built for the physical laboratory of Sorbonne, by La Société Cail, was depicted in the last edition of this book. The normal output of the machine is 2 amperes at a pressure of 3000 volts, but it has yielded a pressure of 4000 volts with ease. There are four armatures of the ring type mounted on the same shaft, each giving a pressure of 750 volts at a speed of 1500 revolutions

---

[1] Address before the Electrical Congress, Chicago, August 24, 1893, *Electrical World*, xxii. 201.

[2] *L'Industrie Électrique*, July 10, 1895, p. 290.

per minute. The winding consists of 160 sections of 66 turns per section, so there are 10,560 wires on the periphery. Each commutator is 20 cm. in diameter, and consists of 160 segments, there being a maximum of 10 volts between any two segments. The resistance of armature is 128 ohms.

Figs. 479 and 480 depict a specially interesting machine of Brown, Boveri & Co., for a high voltage. This is MP 4—20—700—1000 volts—20 amperes.

The chief data of this machine are as follows:—Outside diameter of yoke 35 inches, length parallel to shaft 11·4 inches, of cast-steel. The magnet-cores are circular in section, having a diameter of 7½ inches, and the cores, and at the same time the pole-pieces, are attached to the yoke of the machine by a single steel bolt; the fact that the seatings both at the yoke and pole-pieces are turned and thus possess a rounded surface, making this possible. The armature is 15 inches in diameter, the length between core-heads being 9·85 inches. There are 59 slots and 1416 conductors; there being thus 24 conductors per slot, arranged in the slots in two taped sets of 12 conductors each. Round wire of a section of 0·0037 square inch bare and 0·0070 square inch insulated is used, and the total thickness of insulation between conductors and core amounts to 0·07 inch. The winding has a two-circuit series-parallel grouping described on p. 420; and throughout great attention is given to the insulation of the end turns and connexions. But the design of the commutator is the most noteworthy feature of this machine. Owing to the fact that only twenty amperes have to be collected, the question of insulation was the paramount one to be considered. There are 177 segments, or three per slot; the end clamping plates of this commutator are unusually substantial.

Mica 0·035 inch thick is used between the segments, and the insulating end-rings project far beyond the end of the segments, and are not turned off flush, as is usually the case with machines of lower voltage. On the whole the construction is very simple, that of the commutator especially so; the design being very open throughout and such that there is little chance of dust or dirt collecting, which might lead to a breakdown in the insulation. Fig. 480 gives a sectional view of the armature.

M. Thury, who has consistently advocated the use of continuous currents for the transmission of power,[1] has designed[2] a special machine for an output of 1 ampere at a

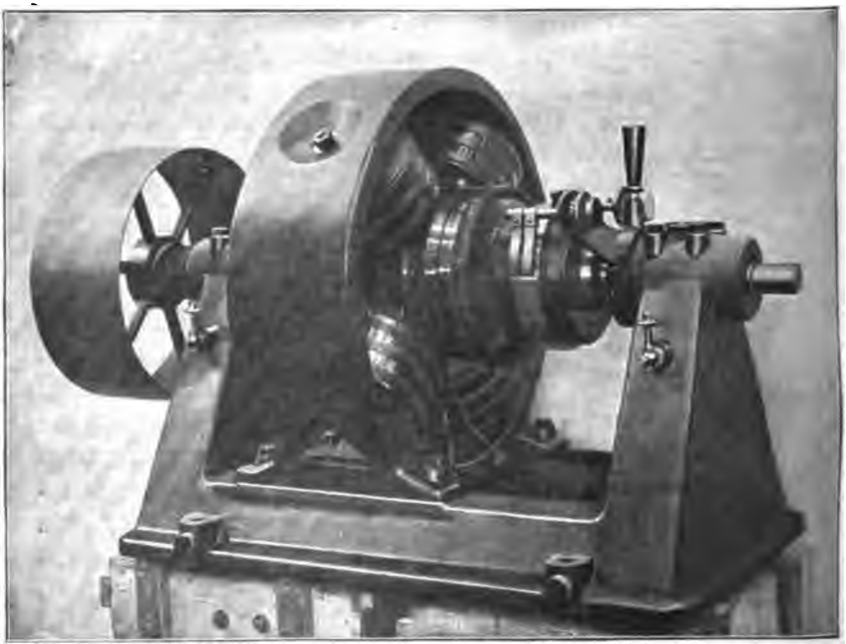


FIG. 479.—HIGH-VOLTAGE DYNAMO OF BROWN, BOVERI & CO.

pressure of 23,000 volts. This is designed with a stationary external armature, and an internally revolving bipolar magnet, the latter being separately excited by a small bipolar machine of ordinary type giving 8 amperes at 80 volts. The armature somewhat resembles the stator of an induction-motor, the winding consisting of 48 coils, lodged in 48 slots in the internal periphery of the ring. Each coil is former-wound

---

[1] See Wyssling in *Elektrot. Zeitschrift*, xxiii., 1003, 1902, for a description of a 340 kilowatt generator working at 2250 volts.

[2] See *l'Électricien*, xxiii. 304, May 10, 1902.

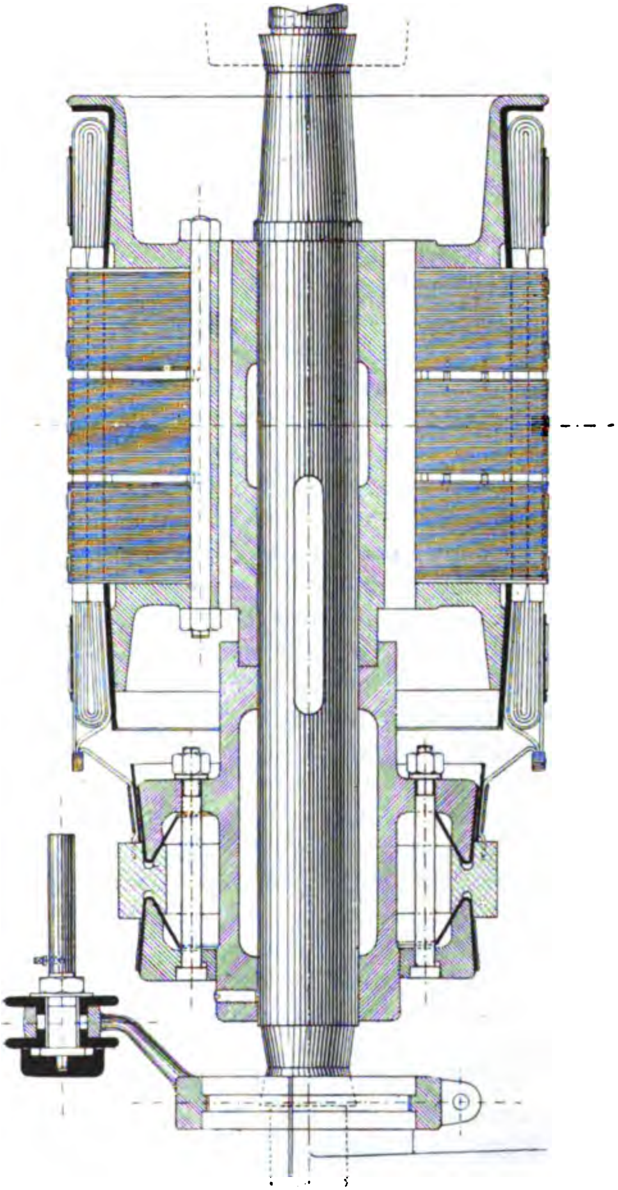


FIG. 480.—ARMATURE OF BROWN'S HIGH-VOLTAGE GENERATOR.

and consists of 500 turns of a silk-insulated copper wire 20 mils in diameter. The slot insulation is of a special paper. The internal resistance of this armature is 700 ohms. The coils are united to one another in a closed circuit, connected symmetrically to a hollow stationary commutator of 96 segments, against the inner periphery of which the two revolving metal brushes make contact. The segments are insulated from one another with an air-space, and at first a blast of air was provided to blow out any short-circuiting sparks. But this device was abandoned in favour of an arrangement of condensers between each segment and its neighbours. The bore of the armature is 22·8 inches. The field-magnet ruus at 600 revolutions per minute.

Very High Speed Machines.—Dynamos driven by steam-turbines, or by motors in motor-generator groups, are commonly required to run at very high speeds, and, therefore, need to be designed with a special view to this circumstance. The utmost pains must be taken to secure perfect balancing of the armature; the commutator segments must be specially secured against centrifugal forces by the addition of an insulated steel ring shrunk over the middle. Carbon brushes cannot be used because of the high peripheral speed, and therefore, cross-compensating windings, p. 266 (on the plan of Ryan or of Déri[1]) upon the field-magnet become a necessity.

Figs. 481 and 482 illustrate a high-speed generator of this type, constructed at the Oerlikon Co.'s works for a motor-generator set. This machine is MP 4—342—1000, giving 570 amperes at 600 volts. As this makes the frequency of magnetization 33⅓ cycles per second, the iron-losses will be greater than usual. The diameter of the armature-core is 27·6 inches, its gross length 11·8. It has 80 slots, each 1·575 deep and 0·53 wide. Each slot contains 6 conductors arranged 2 deep and of section 99 mils × 63 mils. The armature is lap-wound, the pitches being $y_1 = 103$, $y_2 = -101$. The centrifugal force at the armature-face is about 391 pounds' weight per pound. The gap is 0·394 inch. The pole-arc is 73½ per cent. of the pole-pitch. The pole-cores are of special con-

---

[1] British Patent No. 4784 of 1900.

struction, built of stampings in the face of which slots of 1·52 × 0·355 inch in size are stamped out to receive the compensating winding. There are 20 slots in each pole, and in each slot are two conductors joined in parallel, the dimensions of each conductor being 1·26 × 0·118 inch. The shunt wire on the magnets is 189 mils in diameter, covered to 205 mils. The yoke, of steel, is 54·7 inches in external diameter. The commutator has a diameter of 15·75 inches and a total length of 11 inches. There are 240 segments, each 0·176 inch wide at the face. A steel ring is shrunk over the commutator to prevent flying.

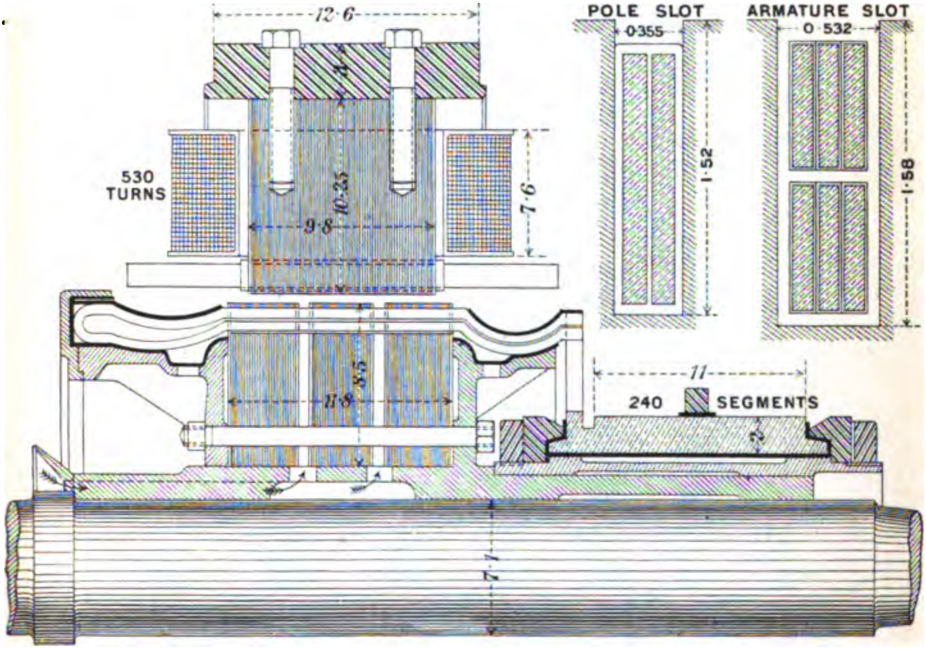


FIG. 481.—OERLIKON CO'S. HIGH-SPEED GENERATOR.

A steam-turbine generator, by Brown, Boveri & Co., is illustrated in Figs. 483 and 484. It is of 100 kilowatts output, and is direct driven by a Parsons steam-turbine at 3500 revolutions per minute. The diameter of the armature body is 13·75 inches and its gross length also 13·75. The peripheral speed is no less than 12,600 feet per minute; and the centrifugal force at the periphery 2400 lb. weight per pound of matter. To hold the conductors in their place requires the very special construction shown of solid gun-metal caps at the ends of the armature. The output is 450 amperes at 220 volts. The commutator, which is surrounded by three steel rings shrunk on, is 7·15 inches in diameter, and no less than 21·65 inches long, its useful length being about 15 inches. This unusual length is due to the circumstance that it is imperative to keep down the surface-speed, which nevertheless is 6500 feet per minute. But more striking is the design of the field-magnet system : for it has no distinctive pole-cores or yokes, but consists of circular stampings pierced with slots through which pass the copper coils, resembling therefore the stator of an induction motor. The external diameter of the structure is 21·5 inches. The magnetizing coils pass through slots surrounding four quadrants, thus creating four poles. The pole-pitch is 10·8 inches, and the equivalent pole-arc about 8·6 inches. Below the magnetizing coils the pole-faces, or rather the whole inner periphery of the system, is pierced with 64 slots to receive a compensating (or cross-compounding) wind-

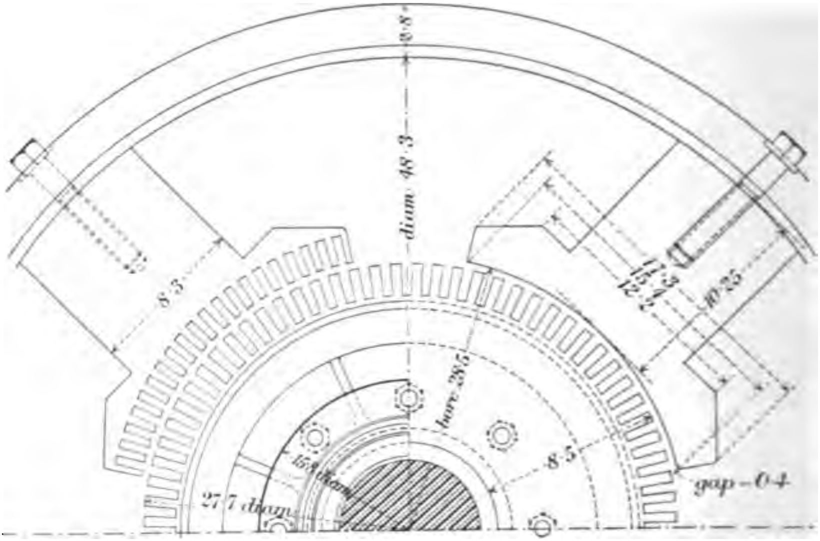


FIG. 482.—OERLIKON CO'S. HIGH-SPEED GENERATOR (SECTION).

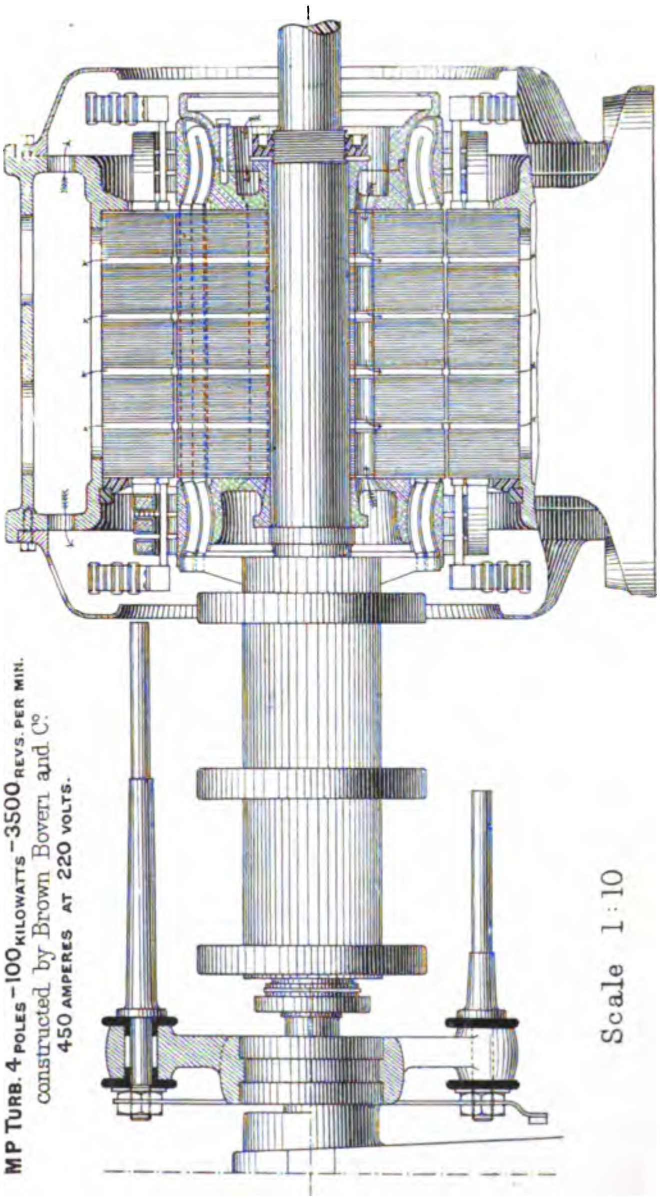

MP TURB. 4 POLES – 100 KILOWATTS – 3500 REVS. PER MIN.
constructed by Brown Boveri and Co.
450 AMPERES AT 220 VOLTS.
Scale 1 : 10

FIG. 483.—BROWN'S 100-KILOWATT GENERATOR FOR STEAM-TURBINE DRIVING.

ing on the method of Déri.[1] Further data of this machine are not accessible, but the flux-density in the gap is about 40,000 lines per square inch, and the specific load of the armature only about 210 ampere-conductors per inch of periphery. With even so low a peripheral density it would be impracticable to construct the machine with so small an air-gap as it has unless it were provided with the compensating winding.

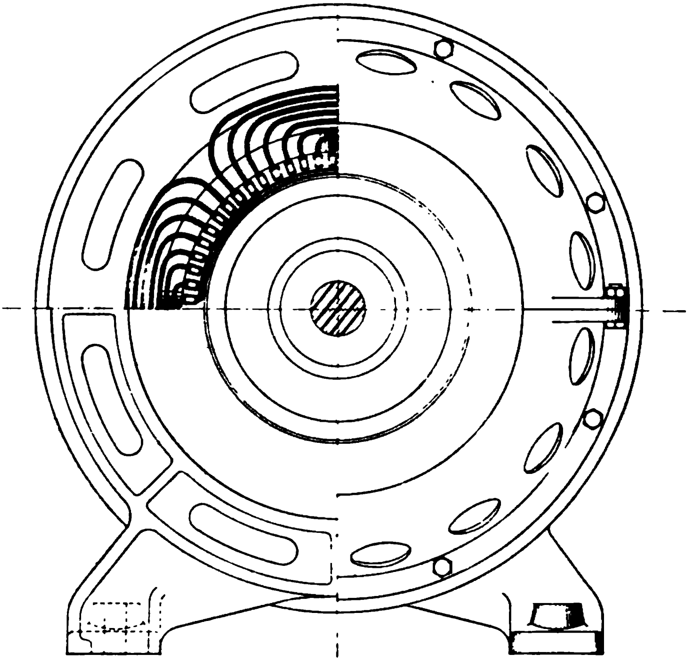


FIG. 484.—BROWN'S STEAM-TURBINE GENERATOR (TRANSVERSE SECTION).

A small steam-turbine dynamo for the purpose of working locomotive head-lights, giving 30 amperes at 33 volts, is described in *Electrical Review* (N.Y.), xlii. 621, May 1903.

Very Low-Speed Machines.—These are of two kinds: (*i*) machines of large output and large size that have to be driven by a water-turbine with low fall; (*ii*) exciters intended to be mounted on the shaft of a large slow-speed alternator.

---

[1] See *Electrotechnische Zeitschrift*, xxiii. 817, Sept. 11, 1902.

The former are distinguished by numerous poles and large diameter: but beyond this there is nothing special in their design, as they generally attain a peripheral speed of normal amount. As to *exciters*, being generally of small output it would be absurd to design them to reach high peripheral speeds.

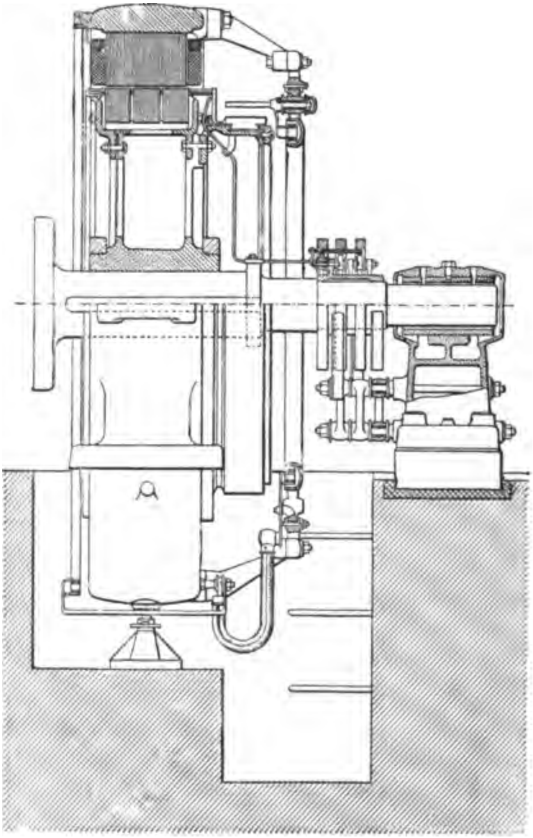


FIG. 485.—DOUBLE CURRENT GENERATOR OF A.E.G.

Hence they are always (relatively to their output) of large dimensions. They generally have 4 or 6 poles, and are frequently wound as series-parallel machines so as to diminish the number of brush sets. An example by Kolben is given on p. 673. Niethammer has discussed the points requiring attention in very high and very low speed machines in the *Elektrot. Zeitschrift,* xxiii. 437, May 15, 1902.

Double-Current Machines.—This name is given to machines provided both with a commutator and with three slip-rings so as to be able to give out at the same time both a continuous-current and a three-phase current. Examples have been described on p. 660, Brown's machine at Alloa, and p. 689, Ganz's marine generator.

A more recent example is that of the generator at the Trafford Park Power Station, installed[1] by The Electrical Co. (A.E.G.) of London. This, as a continuous-current machine would be described, M P 20—600—180, and at this speed the frequency will be 30 cycles per second. This is low, but not too low, for three-phase work: the voltage between the rings being 325 to 355 volts. The armature-core is about 91 inches in diameter and 17 inches in length. Fig. 485 gives a sectional view. The core-rings are built up in 15 segments, of sheets about 20 mils thick, insulated by thin silk paper about 1 mil thick, with an inserted layer of packing paper about 10 mils thick at about every inch. There are also two ventilating ducts. Each segment of the core has 31 slots plus a half-slot at each end, making in total 480 slots, each 1·1 inch deep by 0·216 wide. The winding consists of 480 former-wound coils, each of two separate turns, the conductor being rectangular of a section 118 × 158 mils. In each coil the two turns lie above one another, so that the conductors lie 4 deep in the slot. The winding pitches are $y_1 = 97$, $y_2 = 97$. This makes a wave-winding with 10 paths in parallel through the machine. There are 960 segments in the commutator. The brush rocker for the continuous-current is bracketed out from the yoke, that for the alternating-current is supported from the bearings. For the former carbon brushes are used, for the latter copper brushes. The temperature rise after eight hours' full-load run is guaranteed not to exceed 70° Fahr. The slip-rings are connected to symmetrical points along the windings.

The advantages of double-current machines are: (*i*) that they can furnish currents to both kinds of motors at once ; (*ii*) that they have for equal heating a greater total output than the same machine would afford as a three-phase machine simply ; (*iii*) that while the continuous-current side is excellent for a supply near the station, the three-phase side is available for supplying, through step-up transformers, the distant parts of the system. The disadvantage is that the frequency suitable for three-phase, say 30–50 cycles per second, is too high for a good continuous-current machine, or in other words, the machine must have more poles than is best for a continuous-current machine. At the Montmorency Falls near Quebec, some Westinghouse generators supply continuous-currents at 550 volts to the railway lines adjacent, and two-phase current at 400 volts, with a frequency of about 60 cycles per second, to transformers for transmission to a distant sub-station. Similar machines of 1000 kilowatts each are used for the Third Avenue Railway at New York.

---

[1] See *Electrician,* li. 484, July 10, 1903.

Three-Wire Generators.—In working a three-wire system, at say 220 volts on each side of the middle wire, it is usual to provide two dynamos each of 220 volts, put in series, having therefore the + pole of one joined to the – pole of the other, the middle or neutral wire being led to this common junction. Another plan is to use a single 440 volt generator, and to equip the station with a pair of balancing machines (see next Chapter). To obviate this complication, it has been proposed to create special generators which can furnish two currents (at say 220 volts), with some method of putting the two circuits in series.

There are several methods of doing this :—

1. The dynamo may be built with two identical armatures on one shaft, which may be coupled up as if they were two separate machines, though having but one field-magnet.

2. The armature may be wound with two distinct but identical windings, and have two commutators, one at each end. The brushes may then be coupled up as before.

3. The machine, of full voltage (say 440 volts), may be so designed as to permit a " third brush," or rather a " neutral set " of brushes, to be placed against the commutator half-way

between the + and − brush sets; and to this neutral set the neutral wire of the system is led back. Such machines are known as *three-wire generators.* The problem in such cases is to modify the design so that the collection of current by the intermediate brushes shall be sparkless. To achieve this, it is requisite that a suitable "reversing fringe" shall be provided.

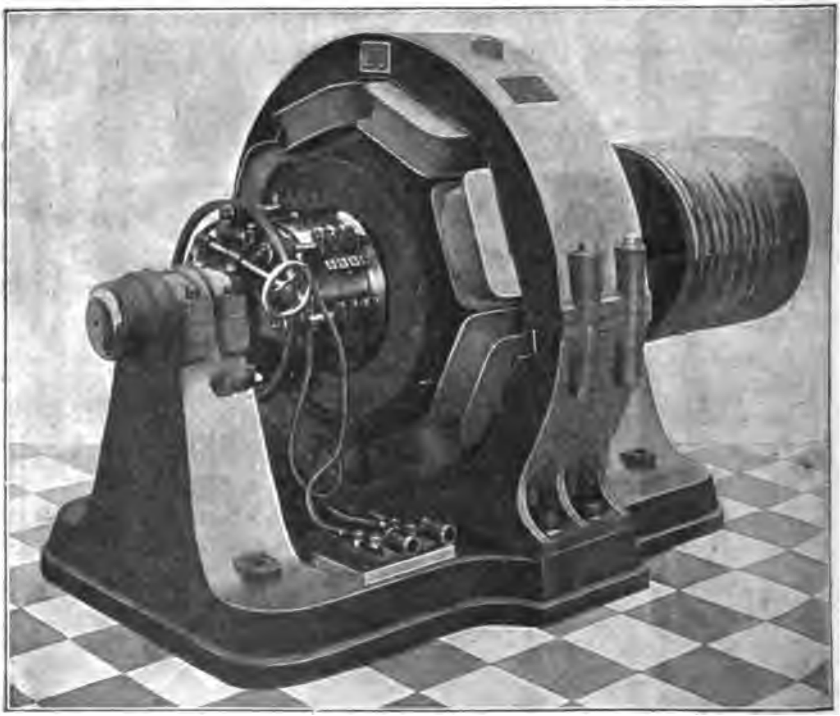


FIG. 486.—THREE-WIRE DYNAMO, BY PÖGE OF CHEMNITZ.

For small machines Sayer's device of notching the pole (p. 707), may suffice. But for large machines it is inadequate. Another suggestion is to divide each pole into two separate parts.

Fig. 486 depicts a special dynamo by Pöge, of Chemnitz, designed for this purpose. This machine has all the properties of two equal generators in series. It gives 150 amperes at 2 × 250 volts, and runs at 500 revolutions per minute. Outwardly it appears like an 8-pole machine, but the pole-cores are so wound that each two successively are of the same polarity, so that it is really a 4-pole machine. The armature winding is a 4-pole winding, and there are 4 sets of brushes placed at the usual positions, 2 positive and 2 negative. But between these there are 4 more brushes at the intermediate positions which are all connected together and are joined to the neutral or middle wire of the system. The magnet winding is also divided into two parts, one part being excited across the outer mains, the other from the middle wire to one of the outers.

Similar machines have been designed by Rothert[1] for Messrs. Lahmeyer. To secure good regulation the forward halves of all the poles should be excited in series with one another by a shunt winding from one side of the mains to the neutral, and the hindward halves excited in series with one another by another shunt from the other side to the neutral.

4. Another way of dividing the whole voltage of a machine into two, thus giving a neutral point at half-voltage between the terminals, is due to Dobrowolsky.[2] He connects the winding to a pair of slip-rings as if to take off an alternating-current, or to three slip-rings as if to make a double-current machine. The slip-rings are then joined together and to the neutral conductor through an equalizer made of two (or three) choking-coils. This method is satisfactory only for differences of load not exceeding 15 to 20 per cent. between the two sides of the system.

For other references to three-wire dynamos, and their extension to multi-voltage generators, see the following :—

Girault, *Éclairage Électrique*, xiv. 204, 1898 ;
Aliamet, *Electrical Review*, xl. 95, 1897 ;
Sengel, *Elektrot. Zeitschrift*, xx. 525, etc., 1899 ;
Rushmore, *Electrical Review* (N.Y.), xxxii. 76, 1898; *American Electrician*, x. 498 ; and *Electrical World*, xxxi. 183, 1898.

Homopolar ("Unipolar") Dynamos.—In those cases where the motion is such that the conductor moves continuously past poles of one kind only, the inductive operation is said to be *homopolar*; in cases where it passes from being opposite a N-pole to being opposite a S-pole, the operation is said to be *heteropolar*. Heteropolar operations obviously generate alternate currents, unless a commutator is added. Homopolar operations give rise to a continuous induction of electromotive-force if the field is also continuous, the rotation of the conductor effecting a continuous cutting of the magnetic lines without any reversal in direction; but in such cases, sliding connexions are necessary to collect the current. Machines giving currents by continuous homopolar induction were formerly known[1] as "unipolar" machines. If the homopolar operation is arbitrarily rendered discontinuous, as in Mordey's alternator, and in some of the "inductor" alternators, by dividing up the pole-face into separate projections, and if the conductor winds alternately backwards and forwards across the field, the result will be an alternating induction.

---

[1] *Elektrot. Zeitschrift*, pt. 17, 1897.

[2] *Ibid.*, 323, 1894 ; and British patent 19423 of 1893.

The earliest machine which has any right to be called a dynamo (Fig. 1, p. 7), namely, the rotating copper disk of Faraday, was, in fact, of the homopolar class. So were his other machines with sliding connexions; for example, the copper cylinder rotating over the pole of a magnet (Fig. 3, p. 8). Plucker[2] devised another form, with a horizontally rotating magnet, having sliding contacts at the middle and at either end. In 1862 Mr. S. A. Varley had a homopolar apparatus with an iron magnet rotating in a vertical frame having a mercurial connexion at the middle-point. About 1878 Dr. Werner Siemens[3] designed a homopolar machine in which there were two cylinders of copper, both slit longitudinally to obviate eddy-currents, each of which rotated round one pole of a U-shaped electro-magnet. A second electro-magnet was placed between the rotating cylinders, with protruding pole-pieces of arching form which embraced the cylinders above and below. Each cylinder, therefore, rotated between an internal and an external pole of opposite polarity, and consequently cut the lines of force continuously by sliding upon the internal pole. The currents from this machine are very great, but of only a few volts of electromotive-force. To keep down the resistance, many collecting brushes press on the cylinders at each end. This dynamo was used at Oker for depositing copper. Much attention has been paid in recent years to machines of this type, and the author himself designed one in which two Faraday disks, coupled at their peripheries outside an internal stationary pole-piece, rotate in a symmetrically uniform field. Mr. Willoughby Smith showed that if an iron disk be used instead of a copper disk a much more powerful effect is obtained. Professor George Forbes has constructed[1] several machines of this class. Originally he began by employing an iron disk which rotated between two cheeks of opposite polarity, the current being drawn from its periphery. He then doubled the parts. The next stage was to unite the two disks into one common cylinder, rotating within an entirely self-contained iron-clad field-magnet. For this reason the inventor prefers to call this type of dynamo "non-polar." A rubbing contact—for which purpose Professor Forbes at one time used carbon brushes, and at another a number of springy strips of metal foil—is maintained at the two extremities of the periphery. One of the earlier forms of machine, with a single disk 18 inches in diameter, was stated to give 3117 amperes at a potential of 5·8 volts when running at 1500 revolutions per minute. One of the later machines, in which the armature is a cylinder of iron 9 inches in diameter, 8 inches long, is designed to give a current of 10,000 amperes at 1 volt, at 1000 revolutions per minute. In designing such machines it is convenient to remember that the voltage may be expressed in the formula

---

[1] This sounds like a *lucus a non lucendo*, for the magnet has two poles. But the name is derived from the term "unipolar induction," which Continental electricians, following Prof. Wilh. Weber, give to the induction of currents by the process of "continuous cutting," which we are now dealing with.

[2] *Pogg. Ann.* lxxxvii. 352, 1852.

[3] *Elektrotechnishe Zeitschrift*, ii. 94, 1881.

$$E = v\,l\,\mathrm{B} \div 10^8\,;$$

where v is the linear velocity of the moving conductor

---

[1] See Specifications of Patent Nos. 3115 of 1883, and 11244 of 1884.

(*inches* per sec.), *l* its length (inches) at right angles to the direction of motion, and B the density of the field. For example, a cylinder of copper, 8 inches broad, revolving in a field of 60,000 lines per square inch, at a linear speed of 800 inches per second, will induce 3·84 volts. The electromotive-force of such machines, at a given number of revolutions, increases as the square of the linear dimensions. All the important forms prior to 1885 are discussed by Uppenborn in the *Centralblatt für Elektrotechnik* of that year, p. 324.

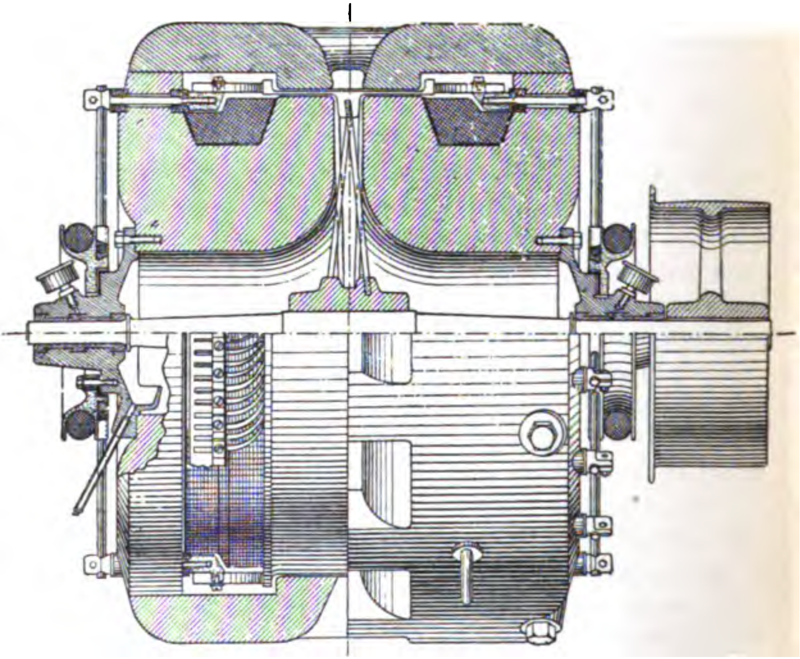


FIG. 487.—BROWN'S HOMOPOLAR DYNAMO.

The theory of the homopolar disk-dynamo has been given by Lord Kelvin,[1] who has shown that such a machine is not self-exciting except above a certain critical speed, dependent on the resistance of the circuit.

[1] On a uniform electric current accumulator (*Phil. Mag.*, January 1868; and *Reprint of Papers*, p. 325).

Two difficulties seem to beset this type of machine, namely, the inherent trouble of peripheral collection of large currents, and the very considerable armature reactions which accompany these large currents, causing great fall in the voltage[1] as the current increases. The latter can only be obviated by the same expedients as hold good in all other types of dynamo, namely, to make the field-magnets relatively powerful and to counterbalance the reactions by compounding or over-compounding the machine by the use of series windings.

Mr. C. E. L. Brown designed the homopolar machine, Fig. 487, built at the Oerlikon Works, with a cylinder of copper rotating between the lips of an iron-clad electromagnet of cast-iron. This machine at 1200 revolutions per minute worked at 10 volts and showed hardly any perceptible drop in voltage when 3000 amperes were taken from it. This is the first really practical homopolar machine.

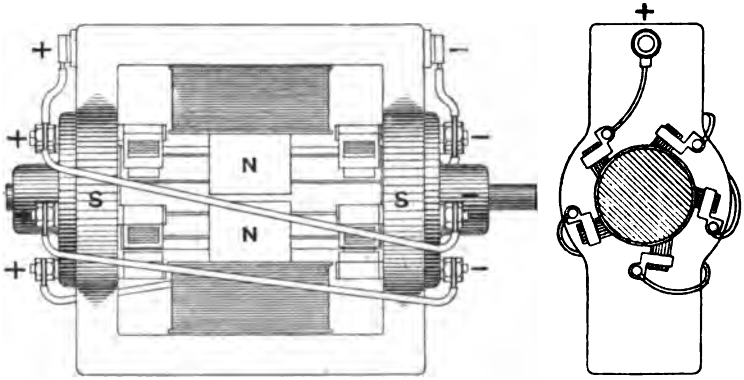


Fig. 488*a*.—Rankin Kennedy's Homopolar Dynamo.

More recent is the machine depicted in Figs. 488*a*, 488*b* and 489, designed by Mr. Rankin Kennedy, which differs in having several conductors under induction united electrically in series through the collecting brushes. This machine has as its armature an iron drum bearing 12 insulated cylindrical segments of copper, revolving at 1200 revolutions per minute in a field of the design shown. The drum is 12 inches in diameter, and with polar faces 12 inches in length; it gave 2000 amperes current at 2·5 volts per bar. There must, however, be two or three times as many bars as those actually active, to avoid short-circuits. The method by which the bars are put in series is shown by the developed diagram, Fig. 489.

---

[1] See some figures given by Hummel in vol. ii. p. 19, of Kittler's *Handbuch der Elektrotechnik.*

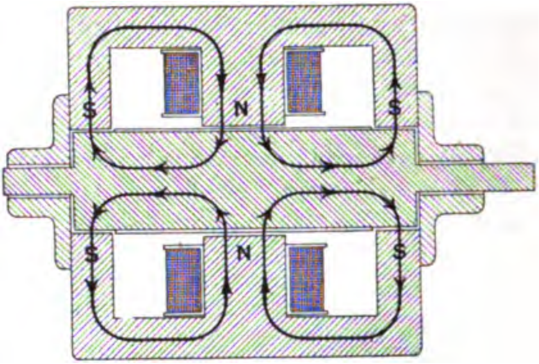


FIG. 488*b*.—RANKIN KENNEDY'S HOMOPOLAR MACHINE (MAGNETIC CIRCUIT)

Other practical forms of homopolar dynamo have been described by H. E. Heath, *Electrical World*, xxxv. 210, 1900, and by F. E. Elmore, British Patent No. 26673 of 1901, this latter being for electrolytic purposes.

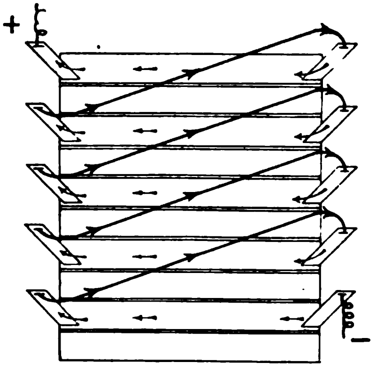


FIG. 489.—DEVELOPED DIAGRAM OF ARMATURE.

The design of homopolar dynamos has been discussed by

Professor Crocker and Mr. Parmly in a paper printed in *Electrical World*, xxiii. 738, 1894, in which they suggest the term "continuous pole" for such machines. They agree with most writers in thinking that conductors of iron or steel are in this type preferable to conductors of copper.

Much interest has been shown in recent years in the homopolar type of machine, the theory of which is still to some extent obscure. It will be sufficient to refer to the writings of Tolver Preston,[1] Hering,[2] Arnold,[3] Hoppe,[4] Puluj,[5] Lecher,[6] Grotrian,[7] and Emde.[8]

Many persons appear still to think that a continuous-current dynamo can be made without either a commutator or the use of sliding connexions. Their ideas are usually futile, because of some fallacious supposition based on imperfect knowledge of principles, such, for example, as that the induction of electromotive-force depends on the flux, whereas it depends on the rate of change of flux.

---

[1] *Phil. Mag.*, February 1885, March 1885, and February 1891.

[2] *Elec. World*, xxiii. 53, 1894.

[3] *Elektrot. Zeitschr.*, March 7, 1895.

[4] *Wied. Ann.* xxix. 544, 1886; and xxxii. 288, 1887.

[5] *Wiener Akad.*, 1888.

[6] *Ib.*, 1894.

[7] *Ann. der Physik.*, vi. 794, 1901; and x. 270, 1903.

[8] *Electrot. Zeitschr.*, xxiv. 577, 1903.

CHAPTER XXIV.

MOTOR-GENERATORS AND BOOSTERS.

MOTOR-GENERATORS are revolving transformers for effecting transformations which cannot be effected by stationary apparatus. They are of two sorts: (1) for transforming a continuous current at any voltage into a continuous current at any other voltage; (2) for transforming continuous currents into alternating currents (single-phase or polyphase) or *vice versa.* In the present chapter we deal only with the continuous-current machinery. In every case the apparatus consists essentially of a combination of a motor with a generator.

CONTINUOUS-CURRENT TRANSFORMERS.

Gramme, in 1874, constructed a machine with a ring-armature wound with two circuits—one of coarse wire, the other with fine wire, having eight times as many turns. Two separate commutators were connected with the two windings. This machine could be used for transforming either from high to low potential or *vice versa.* The same end can be also attained by uniting on one shaft the armatures of two dynamos, one to be used as a motor driving, the other as a generator; and these may have separate field-magnets or a common field-magnet. Such a combination is called a *motor-generator* or *motor-dynamo.*[1] There is very little sparking with such machines, as the reactions in the two sets of coils tend to correct each other. The field-magnet is usually excited as a shunt to the low-potential armature coil. Swinburne has discussed many possible combinations, including one for transforming from a constant-current to a constant-potential condition of distribution. The chief use for continuous current transformers was for many years that of transmission of current at high voltage, so as to economise copper in the feeding mains. In England, continuous-current transformers have been introduced with success by various firms. Messrs. Laurence, Paris and Scott[1] employ a 2-pole machine with cast-iron frame and an armature wound with double circuits. In the Chelsea central station a number of motor-dynamos are used. They have been described in detail by Major-General Webber,[2] and include several types, some being by Laurence and Scott, others of Elwell-Parker construction. In the city of Oxford continuous currents generating 1000 volts are transmitted to motor-dynamos at several points of the city where they feed the network at 100 volts.

---

[1] This name is in strict accordance with the principle of nomenclature which has been (see footnote to page 1) in use for over 35 years, according to which the first part of the compound word refers to the *acting cause* and the second part to the *resulting effect.* In all the machines of this class, whether there is one armature or two, whether there is one field-magnet or two, the motor part is the cause which mechanically drives the dynamo part as a resulting effect. Hence the name *motor-dynamo.* The horrible term *dynamotor*, of Cockney origin, to denote a particular kind of motor-generator, clearly implies some combination, in which a dynamo is the cause of a motor being driven as a result. It therefore logically can only refer to a transmission of power through a line, with dynamo as the cause at one end, and motor as the result at the other. The term is however quite unnecessary, and is falling into disuse.

The following are particulars of an Elwell-Parker bipolar continuous-current transformer, with drum-wound armature but having a commutator at each end.

Fig. 490 shows a small continuous-current transformer constructed by the Crocker-Wheeler Co. for the author, for testing purposes. It transforms a current of 10 amperes at 100 volts to one of 1 ampere

—	Primary.	Secondary.
Volts	1000	110
Amperes	40	360
Resistance of armature winding (ohms)	0·427	0·0052
Conductors around armature	648	72
Segments in commutator	162	36

Speed 500 revolutions per minute.

Field-magnets: shunt-wound with 3080 turns; resistance 8·5 ohms.

Armature core: diameter of disks $16\frac{5}{16}$ in.; nett cross-section of iron 326 sq. in.

Efficiency of double transformation: at full-load 83 per cent.; at half-load 75 per cent.

---

[1] See *Electrician*, xix. 517, October 1887; and *Electrical Review*, xxii. 4, 1888.

[2] *Journal Inst. Electrical Engineers*, xx. 63 to 69, 1891, giving drawings and data of three machines.

at 1000 volts. Mr. T. Parker winds motor dynamos with Eickemeyer coils, the high-pressure windings being completed and connected up first. Then the whole surface is insulated afresh, and the low-pressure windings are laid on in outer layers.

A somewhat different system of continuous-current transformation has been suggested by Cabanellas,[1] and patented by Edison,[2] in which neither armature nor field-magnet revolves, but in which, by means of a revolving commutator, the magnetic polarity of a double-wound armature is continually caused to rotate. In a further modification of this idea, due to Jehl and Rupp, a mass of iron, which completes the magnetic circuit, rotates within the double-wound ring.[3]

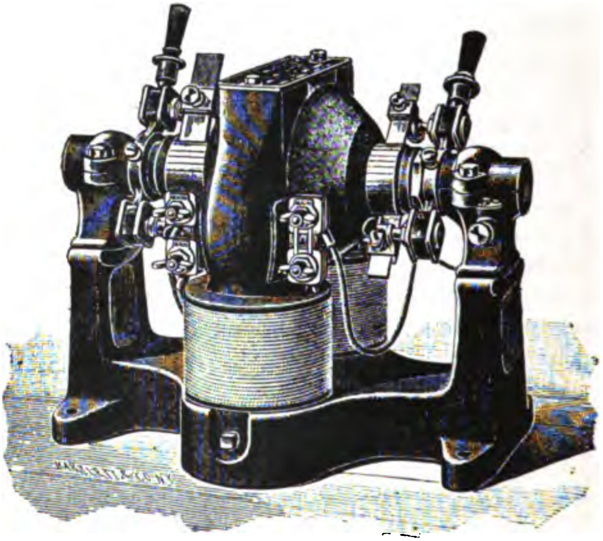


FIG. 490.—CONTINUOUS-CURRENT TRANSFORMER (Crocker-Wheeler Co.).

Spark troubles, however, afflict all merely commutating machines.

For further notices of the methods of continuous current transformation, the reader is referred to articles by Elihu Thomson, in *Electrical World*, x. 108, 1887; by R. P. Sellon, in *Electrician*, xx. 633, 1888; and by Rechniewski, in *La Lumière Électrique*, xxv. 416, 1887; and see *Electrician*, xxxi. 677.

---

[1] See *La Nature*, p. 43, 1882.

[2] Specification of Patent, 3949 of 1882; and *Electrician*, xix. 479, 1887.

[3] See *Electrician*, xix. 514, 1887; xx. 7, 1887; and Specification of Patent 2130 of 1887.

USES OF MOTOR-GENERATOR COMBINATIONS.

The various services for such combined machines may be classified as follows:—

1. Transformation to high voltage for transmission to a distance.
2. Transformation to high voltage for testing.
3. Transformation to low voltage for electro-plating and typing.
4. Equalization of voltages in a 3-wire or 5-wire system of distribution; in which case, the apparatus is termed a *Balancer* (in *German*, *Ausgleichungs-dynamo*).
5. Compensation of voltage drop on long mains or feeders, in which case the machine is termed a *Booster*; or, Prevention of voltage rise on a return main or earth, in which case it is termed a *Negative booster*.
6. Charging a battery of accumulator cells at a higher voltage than that of the supply mains; or for discharging such a battery into the supply mains though they are at a higher voltage than the battery. In such cases, the apparatus is termed a *Battery-booster*; or, if it serves both functions, a *Reversible booster*.

THEORY OF CONTINUOUS-CURRENT TRANSFORMERS.[1]

Let V_1 be the potential at terminals of the primary or motor part, and V_2 that at terminals of the secondary or generator part. Let the C_1, r_1, and Z_1 stand respectively for the armature current, armature resistance, and number of armature conductors of the primary part; and C_2, r_2, and Z_2 for the corresponding quantities of the secondary part. Then the two induced electromotive-forces will be—

$$E_1 = n Z_1 \mathbf{N}, \text{ and } E_2 = n Z_2 \mathbf{N} \text{ ; and}$$

$$E_1 = V_1 - r_1 C_1, \text{ and } E_2 = V_2 + r_2 C_2.$$

Now write k for $Z_1 \div Z_2$ (the *coefficient of transformation*), and we have—

$$k V_2 = V_1 - r_1 C_1 - k r_2 C_2.$$

But the electric work done on and by the armature is equal, assuming loss by eddy-currents and hysteresis to be negligible, or $E_1 C_1 = E_2 C_2$; whence $C_2 = k C_1$, so that the last equation becomes—

$$V_2 = \frac{V_1}{k} - \left(r_2 + \frac{r_1}{k_2}\right) C_2.$$

---

[1] See paper by the Author in *Phil. Magazine*, August 1888.

This shows that everything goes on in the secondary circuit as though the potential were reduced from that of the primary mains in proportion to the respective numbers of windings on the armature: and as though there were added to the internal resistance of the secondary circuit a resistance equal to that of the primary winding divided by the square of the coefficient of transformation. The ratio of transformation is independent of the speed and of the magnetism, though these two quantities depend inversely on one another. If the dynamo (or secondary) part is compound wound the speed may be very nearly constant at all loads; but there is little advantage in this, as the speed always adjusts itself to what is wanted. If the distant generator supplying the system is properly over-compounded it will keep the voltage at the lamps constant, though the transformer is interposed. The objections to the use as transformers of running machines are almost entirely met by the considerations that these machines run sparklessly (owing to the balancing of the self-inductions of the two windings), and with very little friction at the bearings, because the driving and driven parts are both contained in the one rotating part. The brushes once set need not be moved at any load. The effect of the presence of inevitable losses caused by friction, hysteresis, etc., is that the current, C_1, that comes in from the primary mains to drive the motor part of the machine will be increased by just so much as goes to make up the number of watts so lost.

BALANCERS.

For a 3-wire system all that is necessary is a pair of shunt-wound dynamos of a voltage corresponding to the normal pressure between the neutral wire and either of the outers. These two machines are mechanically coupled together, or better still, built on the same shaft, and they are connected across the two sides of the system. If the pressures are normal, the two machines will run idle like unloaded motors, at such a speed that the currents through them are just sufficient to keep up the speed against friction and the reaction of the iron-losses. If, however, the voltage on either half of the system drops, the armature which is across that part will begin to pump in current, tending to keep up the voltage while the second armature at once takes, as a motor, more current from the other half of the system, thus enabling it to drive the first armature. It is of little importance whether the two armatures of the motor-dynamo both revolve in the same field, or whether there are two separate field-magnets. Indeed, a machine having an armature wound double with a commutator at each end will answer admirably.

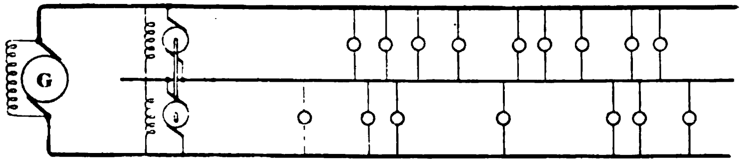


Fig. 491.—Balancer on Three-Wire System.

For a 5-wire system, four identical shunt-wound machines are needed, mechanically coupled up to run at the same speed. If the whole four circuits are at normal voltage, the whole balancer will simply run idle, until by unequal loading of the circuits the voltages become equal. In Fig. 492 the

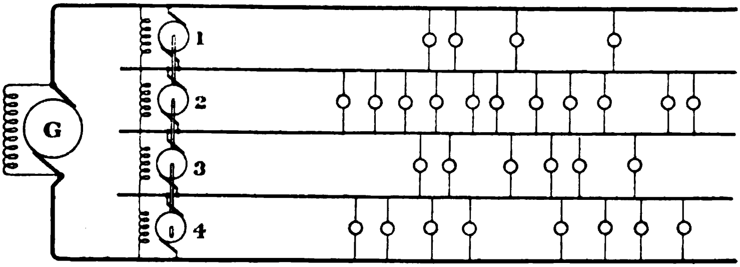


Fig. 492.—Balancer on Five-Wire System.

attempt is made to suggest that the circuits are unequally loaded. In this case, armature No. 2 will be called upon to act as a generator to prevent the voltage dropping, while armature No. 1 will act as a motor, circuit No. 1 being the most lightly loaded, and it will at once drive the machine actively.

The following are particulars of balancers constructed by

Messrs. Mather and Platt for the 5-wire supply in Manchester. The four machines were constructed in pairs as shunt-wound Edison-Hopkinson bipolar dynamos.

Resistance of magnet coils	25 ohms.
Resistance of each armature	0·0126 ohm.

With an output on one side of 126 amperes at 103·4 volts, the output on the generator side was 112 amperes at 100·4 volts. Hence the efficiency of the pair of armatures including all frictional and electrical losses, is 83·5 per cent. Or, looked at from the point of view of the purpose for which the machines were intended, if there be a difference of 3·0 volts between the two sides of the 3-wire system, they will transfer 112 amperes from the higher or less loaded to the lower or more loaded side, so helping to preserve balance.

Fig. 493 depicts a balancer constructed by the Indiarubber and Telegraph Works Co. of Silvertown, for use on a 3-wire network with 500 volts across the outer mains. Each machine is rated as M P 4—87½—550, and will carry 350 amperes as either generator or motor without sparking, and with brushes fixed at the neutral point. The leading dimensions are as follow:—Core diameter 27 inches; core body length 13 inches; number of slots 152, each containing two conductors 0·52 by 0·12 inch in section. The winding is lap, with resistance 0·008 ohm from brush to brush. Shunt resistance 52 ohms; pole span ratio 0·66; field-bore 27·4375 inches. The commutator is 18 inches in diameter, with 152 segments. There are 4 brush sets; in each set 5 carbon brushes 1 × 1 inch in the face. The pole-cores of cast-steel are 11 inches diameter: the yoke is of cast-steel with 50 square inches of section. The flux is about 9 megalines, requiring about 20,000 ampere-turns per pole for excitation.

BOOSTERS.

The method of employing an auxiliary armature in the circuit to raise the voltage, which is the operation now known as boosting, was invented in 1881 by Professor John Perry. The

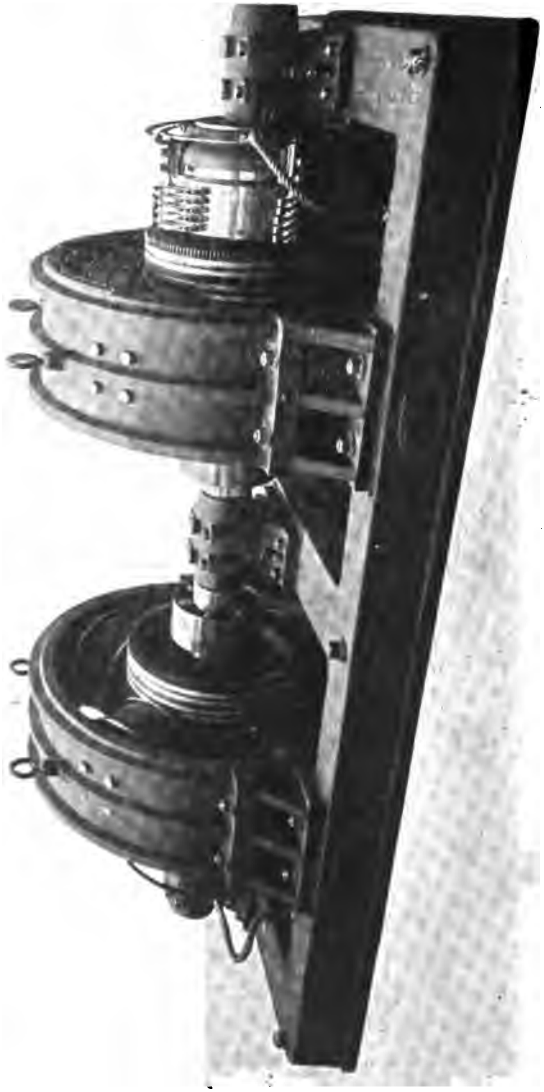


FIG. 493.—BALANCER OF SILVERTOWN CO.

name *booster*, of American origin,[1] denotes a special kind of auxiliary dynamo-electric machine adapted to the purpose of giving to an existing current (which is sent through the armature of the machine) an additional electromotive-force. The French name for a booster is *survolteur* or *machine survoltrice*, the German name is *Zusatz-maschine.* The principal cases in which boosters are needed are: (1) for raising the voltage of the generating mains of a system in order to charge a battery of accumulators; (2) for raising the voltage of some feeder supplying a distant section of a tramway line so as to compensate for the ohmic drop. This last function is to perform for a portion of the circuit the same purpose as over-compounding the generators would effect for the whole supply.

If a booster is used to lower, instead of raising, the electromotive-force, it is sometimes termed a *negative booster* or *dévolteur.* Negative boosters are used (1) to assist an accumulator battery to discharge into the mains from which it was charged; (2) to lower the voltage of some distant section of the return conductors or rails of a tramway line, so as to keep down the voltage in spite of the ohmic resistance.

It is obvious that as a battery of accumulators requires to be alternately charged and discharged, the booster for this service ought to be *reversible*, and for those installations where the battery is used as a buffer to equalize the changes of load, the booster must be *automatically reversible.*

Boosters for Feeders.—The operation of feeder boosters is best explained by reference to a diagram.

Let G G in Fig. 494 represent the generators of a tramway system, so regulated as to keep the station voltage at 500 volts. Owing to the resistance of the line and of the rail return the voltage at distant points will drop below 500 volts, the drop depending on the load, and on its distribution in the system. It is represented as dropping to 450 volts at a distant point. This inequality of voltage cannot be remedied

---

[1] Murray's *New Oxford Dictionary. Boost* (U.S. colloquial): to hoist, to lift or push up from behind. 1860 *New York Herald* says: "Palmerston was boosted into power by the agricultural interest of England."

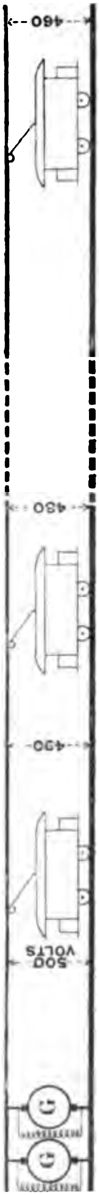


FIG. 494.

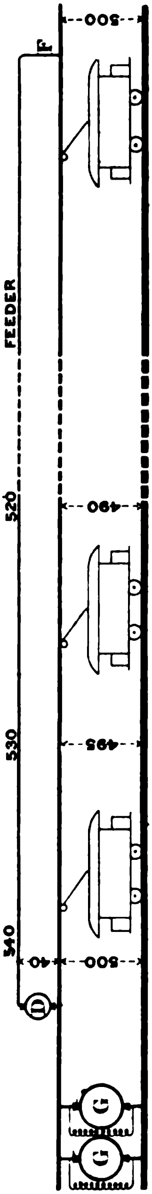


FIG. 495.

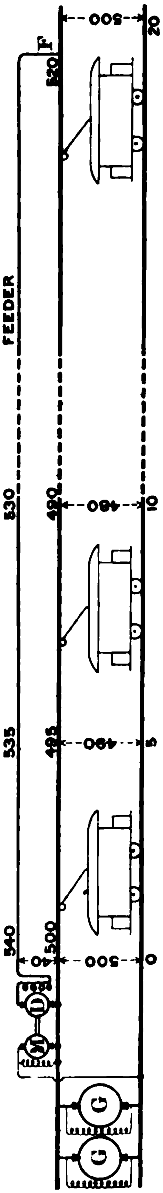


FIG. 496.

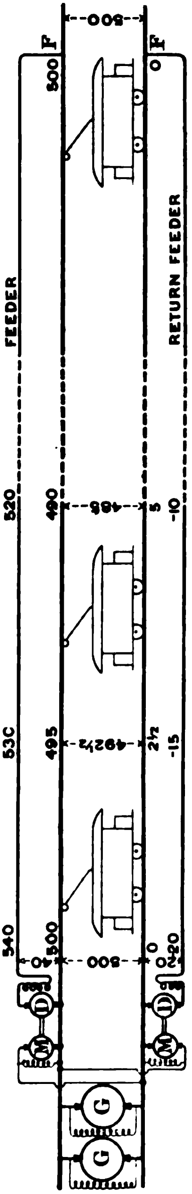


FIG. 497.

USES OF BOOSTERS IN FEEDERS.

by over-compounding the generators, for then the station voltage will at times of heavy load rise above 500. To keep up the voltage at the distant point a feeder is therefore carried from the station to the feeding-point F (Fig. 495), and a portion of the whole current is taken from the mains, and boosted up to a higher voltage by passing it through the armature of an auxiliary dynamo D, which is in the feeder circuit. It is clear that this auxiliary armature must be kept in revolution by an expenditure of power, and that its field-magnets will require to be magnetized. These requirements might be met by driving D by a separate engine, or by mounting it on the end of the shaft of one of the big generators G; and its magnetism might be provided by a shunt from the mains, or by a shunt on itself, or by some separate excitation. But though these things *might* be, the method found appropriate in practice is: to drive D by a shunt motor M supplied from the mains, and to excite its field-magnet in series with itself, as shown in Fig. 496. It then becomes a *booster*. The great advantage of exciting its field-magnet with its own outgoing current is, that then the auxiliary voltage which it furnishes is proportional to the demand for current in the distant section of the system supplied by that feeder. So, for this purpose, the booster is seen to be a combination of a shunt motor with a series dynamo. A perfectly similar combination, but with armature connexion reversed, will serve, as in Fig. 497, as a *negative booster* to reduce the rise of voltage in the return main at a distant point.

The function of a booster in transmitting the station voltage to a distant point on the line cannot be exactly achieved, partly because the magnetism of the field-magnet does not vary proportionally with the excitation, and partly because of reactions in the armature and pole-cores. A series dynamo for such service ought to have laminated cores worked at low saturation.

Instead of employing a series dynamo, an ordinary shunt machine may be used, provided an auxiliary exciter is used to excite the shunt-winding, the field-magnet of the exciter being itself excited by the current going to the feeder. This is shown in Fig. 498, where D is the dynamo, M the motor which drives it, and E the small exciter, the latter being itself driven on the same shaft. Or, an ordinary compound-wound machine may be used, if connected as shown in Fig. 499, its shunt being disconnected and joined to the exciter.

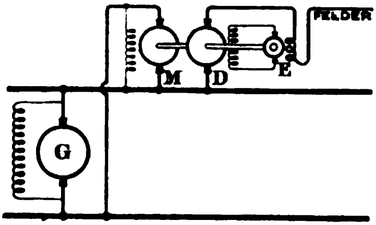


FIG. 498.—SHUNT BOOSTER WITH EXCITER.

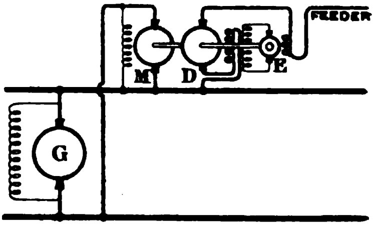


FIG. 499.—COMPOUND BOOSTER WITH EXCITER.

BATTERY BOOSTERS.

As mentioned above, these are of two classes:

(1) *Irreversible Boosters.*
  - (*a*) Shunt booster.
  - (*b*) Series booster.
  - (*c*) Compound booster.

(2) *Reversible Boosters.*
  - (*d*) Differential booster.
  - (*e*) Exciter-controlled booster.

(*a*) *The Shunt Booster.*—This is a simple shunt generator of any kind driven at a constant speed, provided the armature can carry the requisite current. The armature is, of course, in series with the battery, the shunt coil connexions being left as usual, or in other arrangements, are connected straight across the mains. In the first case, Fig. 500*a*, the excitation of the booster depends upon the difference of pressure between the two sides of the booster, which varies, varying the current through the shunt. In the second case, Fig. 500*b*, the shunt receives a constant current from the omnibus bars, and

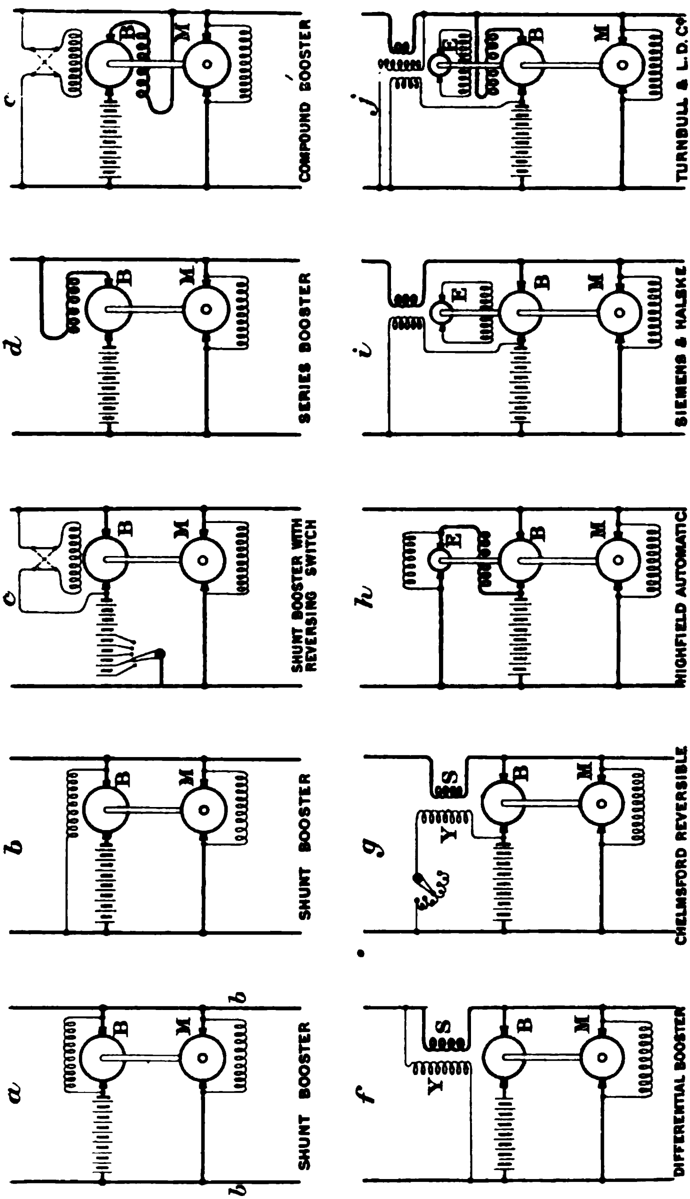


FIG. 500—BATTERY BOOSTERS.

consequently the number of volts boosted is also constant. When, in order to charge the cells, the voltage is to be raised above that of the 'bus-bars, the field coils of the booster must be switched in so that the voltage of the booster is added to that of the 'bus-bars ; but for discharge the connexions must be reversed, so that in this mode of operating a reversing switch needs to be added, as in Fig. 500*c*.

Another mode of operating is to cut the booster out of circuit when the cells are charged, and then simply discharge the cells as required into the mains. But in this case some additional regulating device is needed for the batteries during discharge. This regulating device takes the form of end cells, more cells being switched in as the pressure falls, as in Fig. M, or instead as regulator there may be used to produce a back pressure, a few cells containing simply substantial lead plates which are never drawn upon for current, but merely reduce the voltage of the battery during the first period of discharge, and are switched out one by one as the voltage of the cells falls.

(*b*) *The Series Booster.*—This is simply a series-dynamo driven by motor or otherwise, at a constant speed, Fig. 500*d*. The additional voltage it provides will obviously vary with the current through it, though not in exact proportion. As the sign of the induced electromotive-force will change with that of the current through the magnet coils, no reversing switch has to be provided. Girault has shown how to reckon out suitable resistances for a non-automatic regulation.

It will be noted that neither *a* nor *b* fulfils the conditions for automatic working, since *a*, though fairly automatic during either charging or discharging, needs a reversing switch to be operated when changing over from charge to discharge, or *vice versa* ; while *b*, though automatic as to this latter requirement, gives the least boost at the time when most is needed.

(*c*) *The Compound Booster.*—This, as depicted in Fig. 500*e*, is simply an ordinary compound-wound machine. Its series coils may be inserted either in series with the armature or in the feeder circuit which it supplies, and the shunt be connected in either of the ways described under *a*. The shunt naturally requires a reversing-switch, and therefore the operation is not automatic. The regulation effected is a little closer than that afforded by either *a* or *b* alone.

(*d.*) *Differential Booster.*—If the directions of the shunt and series-exciting currents of a compound booster are reversed, so as to act differentially, the action of the booster becomes reversible and automatic, though the regulation is still imperfect. The connections may be as in Fig. 500*f* or Fig. 500*g*, where Y denotes the reversed shunt coil. The coil Y must be capable at a time when little current is going through the series coil to the feeder, of so magnetizing the booster magnets as to add the voltage of the armature B to that of the 'bus-bars, and so charge the battery. If the demand increases, the action of S which opposes Y reduces the magnetization and the added voltage. At one particular load on the feeder the two will neutralize one another, and the booster will, at that stage, help neither to charge nor to discharge the cells. As the feeder-load still further increases, the coils S will preponderate over Y, the magnetism will reverse, and the booster will help to discharge the cells into the feeder. The shunt may be connected (Mailloux) across the battery, or (Crompton) across the mains as in Fig. 500*g*. In a further modification (Entz) there are two series coils, one in the feeder, the other in the circuit from the 'bus-bars, and a rheostat is added to adjust the balancing effect of the reversed shunt.

(*e.*) *Exciter-Controlled Booster.*—A species of booster in much favour is that having its field-magnets supplied with current from a third machine, an *exciter* (itself driven at a constant speed, either independently or on the booster-shaft) the regulation of the booster being effected by regulating the field of the exciter. Of this kind are the automatic reversible boosters of Siemens and Halske, Highfield, Hubbard, and Turnbull. Exciter-controlled boosters are depicted in Figs. R, S, and T. In Highfield's (Fig. 500*h*) the exciter is a small shunt machine, supplying current to the field-magnets of the booster armature. The circuits are arranged so that the current through the coils of this field-magnet is proportional to the difference between the voltage of the battery and that of the exciter. During charge the voltage of the battery is higher, during discharge lower than that of the exiter. Hence the excitation of the booster automatically reverses between charge and discharge. The voltage of the exciter ought therefore to be adjusted to be equal to the mean or neutral voltage of the battery, or about 1·95 volts per cell. In Siemens and Halske's (Fig. 500*i*) the magnet-coils of the booster are supplied direct from the armature of the exciter; the excitation of the latter being differential, partly by a shunt to the battery, partly by a series coil in the feeder circuit. In Hubbard's, the exciter circuit is the same as in Highfield's, but the motor instead of being shunt-wound has a thick wire magnetizing coil inserted in the feeder-circuit. The booster of Turnbull and the Lancashire Dynamo Co. (Fig. 500*j*) has a differential field-magnet for the booster armature, one set of coils being in the charging circuit, the other in the circuit of the exciter armature; and the excitation of the exciter magnet is like that of Siemens and Halske with the addition of a third coil which is shunted across the 'bus-bars.

The advantage of the automatic reversible variety of booster is that on a very variable load such as that of a tramway system a battery may be used to give out all the current needed above a certain fixed amount; and automatically takes in all surplus current from the generators whenever the load falls below this amount. The share of load that falls on the generating plant thus becomes absolutely constant, enabling the plant to be worked with much increased efficiency. The subject was discussed by Highfield and others at length in the *Journal of the Institution of Electrical Engineers*, xxx., 1040, 1901.

The following references to the literature of the subject will be useful:—

Prescott, *Trans. Amer. Inst. El. Engineers*, vi., 1889.
Mailloux, *U.S. Patent* No. 430,868 (1890).
Crompton and Chamen, *British Patent* 7252 of 1892.

Sayers, *Electrical Review*, xxxiii. 66, July 1893.
Highfield, *Journ. Inst. El. Engineers*; also *British Patents* Nos. 537 of 1899 and 12,972 of 1900.
Entz, *U.S. Patents* Nos. 625,098, 625,099, 625, 100, 670, 476.
Scott, *Street Railway Review*, January 15, 1896.
Zander, *Elektrot. Zeitschrift*, August 1896.
Woodbridge, *Journal Franklin Institution*, May 1898.
Lamme, *English Patent* No. 8142 of 1898.
Girault, *L'Industrie Électrique*, xxxiv. May 25, 1899.
Lyndon, *Electrical World*, xxxviii. 13, July 6, 1901; and *U.S. Patent* No. 648,874.
Hubbard, *American Electrician*, xii. 85, February 1900; and *U.S. Patents* Nos. 640,565, 651,664, and 673,266.
American Electrician: see articles September 1899, p. 441; January 1901, p. 47; March 1901, p. 136; April 1901, p. 195; May 1901, p. 239; and November 1901, p. 524.
Macrae, *Electrical World*, xxv. 431.

Useful combinations of boosters with balancers on the three-wire system are described by G. Stephens in an article in the *Electrical Engineer*, xxxii. 6, July 1903.

Thury has described an automatic booster regulator of a somewhat different sort. The booster armature, Fig. 501, is magnetized differentially by a series coil in the charging circuit, and a coil shunted across the battery, into the circuit of which is introduced a rheostat automatically moved by a regulator (see Fig. 537, Chapter XXVI.), controlled by a solenoid shunted across the 'bus-bars.

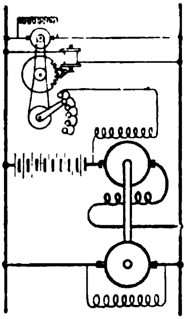
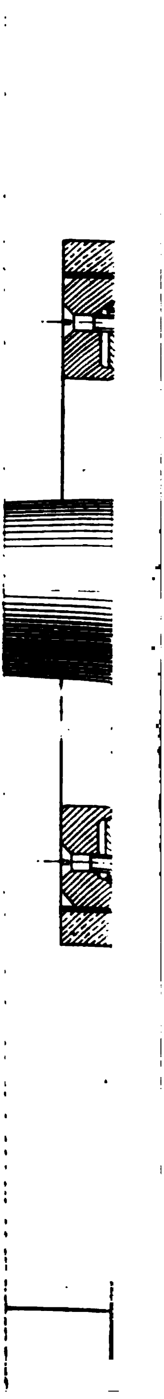


FIG. 501.—THURY'S AUTOMATIC REGULATOR BOOSTER.

Five very remarkable booster sets, designed by M. Thury, have been furnished by La Compagnie de l'Industrie Électrique, of Geneva, to the sub-station of Porta Volta of the city of Milan. These machines are 6-polar, driven by a 6-pole motor, each booster armature having two independent windings and two commutators, so that if the armatures are coupled in series they can carry a current of 2000 amperes, with a boosting voltage of 100 volts,

he Ele



or, if in parallel they can carry 4000 amperes with a boosting voltage of 50 volts. Fig. 502 depicts the apparatus.

Figs. 503 and 504 depict another apparatus designed by M. Thury, of a different character, namely, a small generator, shunt-wound, having on the end of the shaft a second smaller armature, revolving in a separate field excited in series. This second armature is for boosting a portion of the current for charging a battery of accumulators. The arrangement, which is intended for hotels and isolated installations, is interesting as showing the relation between *boosting* and *compounding*. If the whole current had to be boosted the series winding might have been put on the field-magnet of the generator, and one armature would suffice.

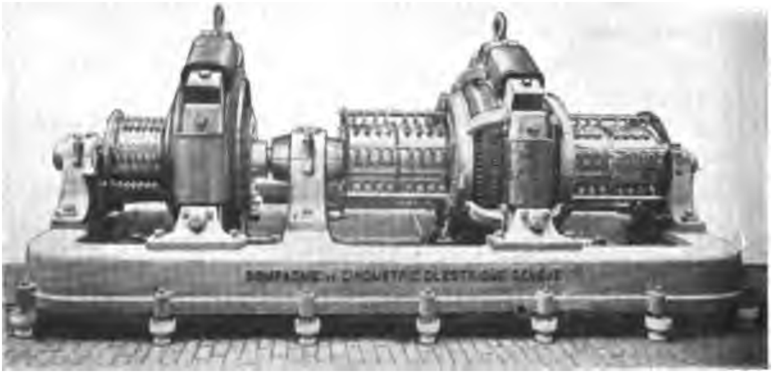


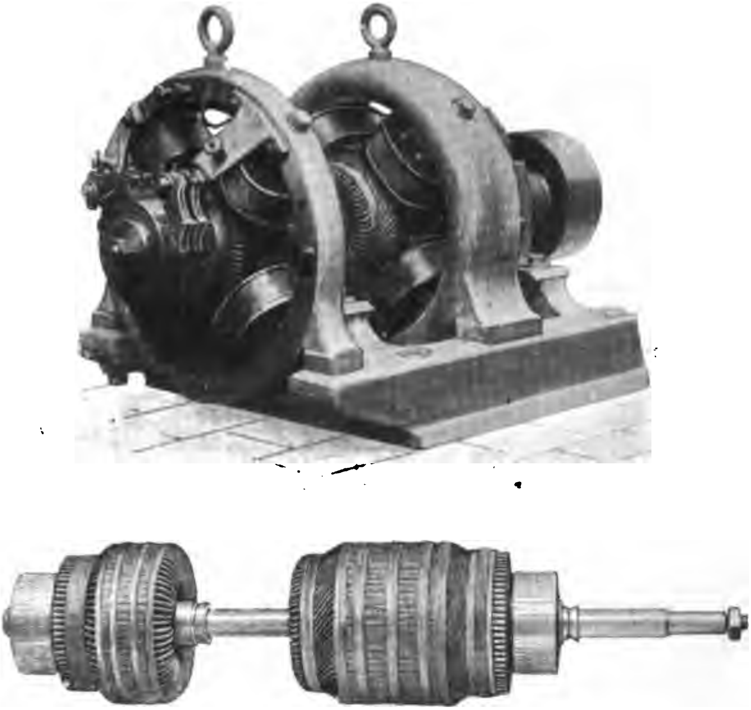
FIG. 502.—THURY BOOSTER (MILAN), FOR GIVING 50 VOLTS ADDITIONAL PRESSURE TO 4000 AMPERES.

Plate XXX. depicts a large booster constructed by the Elektrizitäts Aktien Gesellschaft, of Frankfurt (formerly the Lahmeyer Co.), for the Charing Cross Supply Company, for taking a current of 1000 amperes at 200 volts and boosting it up to 260 volts. The booster proper would, therefore, be described as a 60 kw. separately excited generator. It is driven by a shunt motor which takes about 72 kw. of power, namely 360 amperes at 200 volts. Both machines are 6-polar. As one armature has to carry about three times as much current as the other, and at about one-third the voltage, they are designed to have the same size of slot and the same size of conductor, the motor armature having a wave-winding with two circuits, and the booster armature a wave-winding with six circuits in parallel. The machine runs at 550 revolutions per minute. The following are the principal dimensions in millimetres:

—	Motor.	Generator.
Armature.		
Number of slots	100	90
Breadth of slot	8·2	8·2
Depth ,,	32	32
Diameter of core	670	682
Length ,,	240	240
Air-gap	7	6
Size of conductor, bare	6 × 12	6 × 12
Conductors per slot	2	2
Winding pitches front	+ 33	+ 29
Winding pitches back	+ 33	+ 29
Segments of commutator	100	90
Field-Magnet.		
Number of bobbins	6	6
Arrangement of bobbins	in one series	in one series
Diameter of wire	1·2 bare 2·1 covered	2 bare 2·3 covered
Turns per bobbin	1410	1200
Maximum exciting current	4	5

DESIGN OF BOOSTERS.

From the foregoing considerations, it will be evident that the design of boosters involves some departures from that of other continuous-current machines. They have to deal with heavy currents, and therefore require very large commutators, often double commutators. They have to generate low electromotive-forces, and therefore have some points in common with machines for electrotyping. To keep the resistance low and to subdivide the current between several sets of brushes, the design should be multipolar. There should be ample section of iron in the magnets, and the flux-density should be low so as to keep the field strength fairly proportional to the current. As the booster is rarely working at its maximum current, the current density in the copper may be very high. In reversible boosters the whole of the iron of the magnets should be laminated to ensure quick reversal. In these machines, with their field necessarily weak even at times when the armature-current is large, the reaction of the armature becomes very important, and spark-troubles arise unless the greatest care is taken in the design. They ought to be compounded, and indeed would be better if cross-compounded on the plan of Ryan or of Déri.



FIGS. 503 AND 504.—GENERATOR WITH BOOSTER ARMATURE ON THE SAME SHAFT (SURVOLTEUR).

CHAPTER XXV.

CONTINUOUS-CURRENT MOTORS.

HAVING dealt with the dynamo in its function as a generator of currents, we now come to its converse function, namely that of converting the energy of electric currents into the energy of mechanical motion.

An electric *motor*, or as it was formerly called, an *electro-magnetic engine*, is one which does mechanical work at the expense of electrical energy furnished to it through conducting mains from some external source.

It is impossible within the limits of this work to deal with the various stages[1] of discovery and invention. The work of Page, Davidson, Hjorth and others is alluded to in the Historical Notes at the beginning of this book. But the real development came after the commercial introduction of Gramme's dynamos in 1871, as engineers began to understand how two machines could be used—one as generator, the other as motor—to transmit power through a line.

All the earlier attempts to introduce electric motors came to nothing, for two reasons. Firstly, at that time there was no economical method of generating electric currents known; secondly, the great physical law of the conservation of energy was not fully recognised, and its all-important bearings upon the theory of electric machinery could not be foreseen.

---

[1] An excellent account of the early forms of electric motor, both European and American, is to be found in Martin and Wetzler's *The Electric Motor and its Applications*, third edition, 1891. All readers interested in the subject should also consult the paper on *Electro-magnetism as a Motive Power*, by the late R. Hunt, in *Proc. Inst. Civil Engineers*, xvi. April 1857, together with the discussion that followed it, in which part was taken by Professor Thomson (now Lord Kelvin), Mr. (afterwards Sir William) Grove, Professor Tyndall, Mr. Cowper, Mr. Smee and Mr. Robert Stephenson. For modern motors they should consult Kapp's *The Electric Transmission of Power*, Snell's *Electric Motive Power*.

While voltaic batteries were the only available sources of electric currents, economical working of electric motors was hopeless; for a voltaic battery wherein electric currents are generated by dissolving zinc in sulphuric acid is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work,[1] an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

The fact, however, which seemed most discouraging, but which, if it had been rightly interpreted in accordance with the laws of conservation of energy, would have been found most encouraging, was the following:—If a galvanometer was placed in the circuit with the electric motor and the battery it was found that when the motor was running the battery was unable to force through the wires so strong a current as that which flowed when the motor was standing still. The faster the motor ran, the weaker did the current become. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or else a counter electromotive-force. At first, the common idea was, that when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi[2] enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter electromotive-force (or "electromotive-force of reaction") which was developed. In fact, the theory of the conservation of energy requires[1] that such a reaction should exist. Joule,[2] by further experiment, found that the counter electric action is proportional to the velocity of rotation and to the magnetism of the magnets.

---

[1] A convenient way of regarding the economic question from the point of view of the cost of the voltaic battery is afforded by the following calculation. Supposing the electric motor to convert all the electric energy of the battery without loss into mechanical energy, the amount of zinc used per horse-power in one hour will be almost exactly two pounds divided by the volts of electromotive-force of the cell employed in the battery.

[2] *Mémoire sur l'application de l'électromagnétisme au mouvement des machines* par M. H. Jacobi (Potsdam, 1835).

Two points are vital to the right understanding of the action of electric motors: (1) The propelling drag; (2) the counter electromotive-force. The first is that the real driving-force which propels the revolving armature is the drag which the magnetic field exerts upon the armature wires through which the current is flowing, or, in the case of deeply-toothed armatures, on the protruding teeth: the second is that the revolving armature generates a counter electromotive-force as its moving wires cut the magnetic lines.

The Propelling Drag.—In Chapter IX., on the mechanical actions in armatures, the drag, which a magnetic field exerts on a conductor carrying a current, has been explained, and calculations about its magnitude given. In a generator the drag acts in a direction which opposes the rotation, and is, in fact, a counter-force or reaction against the driving force. In a motor the drag is the driving force, and produces the rotation. In machines with toothed cores and sunk windings this drag comes almost entirely upon the iron teeth.

The Counter Electromotive-force.—Let it be remembered that wherever in an electric circuit, current flows through some portion of the circuit in which there is an electromotive-force, the current will there either receive or give up energy according to whether the electromotive-force acts *with* the current or *against* it. This will be made clearer by Fig. 505 representing a circuit in which there are a dynamo and a motor. Each is rotating right-handedly, and therefore generates an electromotive-force tending upwards from the lower brush to the higher. In each case the upper brush is the positive one. But in the dynamo, where energy is being supplied to the circuit, the electromotive-force is in the same direction as the current; whilst in the motor where work is being done, and energy is leaving the circuit, the electromotive-force is in a direction which opposes the current. There ought to be no difficulty in understanding that this electric reaction is an essential of motor working.

---

[1] For a simple explanation of the necessity of a counter electromotive-force, see the author's *Elementary Lessons in Electricity and Magnetism* (edition of 1900, p. 443).

[2] *Annals of Electricity*, viii. 219, 1842, and *Scientific Papers*, p. 47.

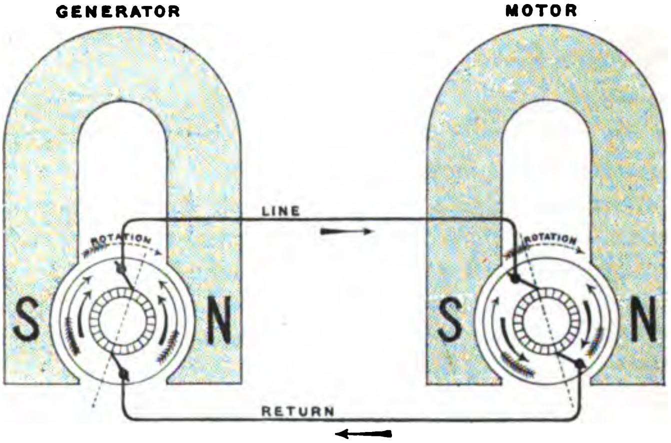


FIG. 505.

Consider the converse case, when we are employing mechanical power to generate currents by rotating a dynamo. Directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately requires much more power to turn the dynamo than is the case when no electric work is being done. In other words, there is an opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive-force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive-force is a "counter electromotive-force."

The experiment of showing the existence of this counter electromotive-force is a very easy one. All one requires is a little motor with a powerful field-magnet,[1] a few cells of battery of small internal resistance, and an amperemeter. They should be connected up in one circuit, and the deflexion of the amperemeter should be observed when the motor is held fast, and when it rotates with small and large loads. In an experiment, made on a motor with separately-excited magnets, the following figures were obtained :—

Revs. per min. . .	0	50	100	160	180	195
Amperes . . .	20	16·2	12·2	7·8	6·1	5·1

Apparently, if the motor had been helped on to run at 261½ revolutions per minute, the current would have been reduced to zero. The current of 5·1 amperes was needed to drive the armature against its own friction at the speed of 195.

Upon the existence and magnitude of this counter electromotive-force depends, in fact, the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In discussing dynamos as generators, many considerations were pointed out, the observance of which would tend to improve their efficiency. It is needless to say that such considerations as the avoidance of useless resistances, unnecessary metal masses in cores, and the like, apply equally to motors. The freer a motor is from such defects, the more efficient will it be. But the efficiency of a motor in utilizing the energy of a current depends not only on its efficiency in itself, but on another consideration, namely the relation between the electromotive-force which it itself generates when rotating, and the electromotive-force or electric pressure at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive-force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive-force.

---

[1] One of any ordinary type—a magneto-machine or a series-wound motor will answer.

ELEMENTARY THEORY OF ELECTRIC MOTIVE POWER.

It will be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current, depends upon the ratio between the counter electromotive-force developed in the armature of the motor and the electromotive-force of the current which is supplied by the battery. No motor ever succeeded in turning into useful work the whole of the energy that is supplied, for it is impossible to construct machines devoid of friction or to obtain conductors devoid of resistance; and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the wires that offer the resistance. Let the symbol W stand for the electric power supplied by the mains to an electric motor, and let w stand for that part which the motor takes up as useful power from the circuit.[1] These symbols may stand for the numbers of *watts* respectively supplied and utilized. All that part of the energy of the current which is not utilized by the motor, and transformed into useful work, will be wasted in useless heating of the resistances. The watts lost in heating will therefore be equal to $W - w$.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, w must be as nearly as possible equal to W. It will be shown mathematically that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter electromotive-force of the motor and the electromotive-force of supply. (As it is not wished here to complicate general considerations by introducing into the expression for the efficiency the energy wasted in heat in the field-magnet coils of the motor, we here assume that the magnetism of the field-magnets is independently excited.) The proof will be given later. Let us denote this whole electromotive-force with which the mains supply the motor (i. e. the volts measured across the terminals of the motor) by the symbol V, and let us call the internal counter electromotive-force E. Then the rule is

---

[1] The symbol w must be clearly understood to refer to the power taken up by the motor, *as measured electrically*. The whole of this power will not appear as useful mechanical effect however, for part will be lost by mechanical friction, and a minute percentage also in the wasteful production of eddy currents in the moving parts of the motor. What proportion of w appears as useful mechanical power depends on the efficiency of the motor *per se*, which we are not here considering. In all that immediately follows we shall suppose such causes of loss not to exist, or the motor will be considered as a perfect motor.

$$\frac{w}{W} = \frac{E}{V}.$$

But we may go one stage further. If the motor be prevented from turning, the current, as calculated by Ohm's law, would be

$$C_o = \frac{V}{R}.$$

If the resistances of the circuit are constant, the current C, observed when the motor is running, will be less than C_o.

$$C = \frac{V - E}{R},$$

where R is the total resistance of the circuit. Hence

$$\frac{C_o - C}{C_o} = \frac{E}{V} = \frac{w}{W}.$$

From which it appears that we can calculate the efficiency of which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength. Though this mathematical law of efficiency had been known for forty years it was for long ignored or misunderstood. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, was given instead. A machine does not generally do its work with the best economy when it performs the greatest work in the least possible time; and the maximum economy or efficiency of an electric motor is not necessarily when its output is at a maximum.

Jacobi's law concerning the maximum power of an electric motor supplied with currents from a source of given electromotive-force is the following:—The output of power by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter electromotive-force of the motor is equal to half the electromotive-force of supply. Now, under these circumstances, only half the energy furnished by the external source is utilized, the other half being wasted in heating the circuit. If Jacobi's law was indeed the law of efficiency, no motor, however, perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work. And if it were to waste half its energy on heating itself its insulation would at once be burned out. In fact, if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before. Or, instead of gearing it up to run fast, we may gain the same advantage by strengthening its field-magnets.

The true law of efficiency was clearly stated by Lord Kelvin in 1851, and is recognised in a paper by Joule at about the same date. Jacobi seems very clearly to have understood that his law was a law of maximum working, but not to have understood that it was not a law of true economical efficiency. Jacobi's law is not a law of maximum efficiency, but a law of maximum output; and that is where the error creeps in. It is significant, in suggesting the cause of this remarkable conflict of ideas, that throughout the memoir which he published in 1852, Jacobi speaks of *work* as being the product of force and velocity, not of force and displacement. The same mistake is common enough among Continental writers. Now the product of force and velocity is not work, but work divided by time, that is to say, "power," or "rate of working," or "activity" This may account for the widely-spread fallacy. M. Mascart in 1877 pointed out in the *Journal de Physique*, p. 205, how in a magneto-electric machine the efficiency rises with the speed up to a limiting value; and he discussed the efficiency of various types of generators and motors, and of the transmission of power between two machines. In a paper by Achard in the *Annales des Mines* in January 1879, a clear distinction is drawn between the maximum activity and the efficiency of a motor, and he points out how as the latter increases to a maximum, the former falls to zero. In April, Sir C. W. Siemens and Lord Kelvin gave evidence on electric transmission before a Parliamentary Committee, the latter showing that it was possible to transmit 21,000 H.P. through a copper wire ½-inch in diameter, to 300 miles, provided a potential of 80,000 volts was used. Later in the same year Professors Elihu Thomson and Houston, basing their remarks upon the suggestions of Kelvin and Siemens, proposed to obtain economic results by connecting in series several dynamos at one end of a line, and several motors at the other, so as to work with small currents and high electromotive-forces. The advantage of high voltage in both dynamo and motor at the two ends of the line was never better or more clearly put than by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association, in Sheffield in August 1879. These high voltages he proposed to obtain not by increasing the magnetism but by increasing the speed, and by separate excitation of both dynamo and motor. The gain in economy by allowing the motor to run at a high speed with efficiency increasing as its speed increases, was also pointed out by Dr. Werner von Siemens in his address to the Naturforscher meeting in September 1879 (see Werner von Siemens' *Wissenschaftlichen und Technischen Arbeiten*, ii. 374).

Theory of Motors.—If V be the electromotive-force of the mains supplying the current to the motor when the motor is at rest, and C be the current which flows at any time, the whole electric power W expended will be the product of the whole of the applied volts multiplied by the whole of the amperes, or,

$$\text{(Total watts) } W = VC = V\frac{(V - E)}{R}; \qquad [1]$$

where R is the resistance through the armature of the motor.

Now, when the motor is running, part of this electric power is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. The useful part may be similarly written down, as the product of the armature's own volts (the counter electromotive-force) and the amperes, or

$$\text{(useful watts) } w = E\,C = E\frac{(V - E)}{R}. \quad . \quad [\text{II}]$$

All the power which is not thus utilized is wasted in heating the resistances. So we may write—

Power supplied = power utilized + power wasted in heating

or, W = w + watts wasted in heating.

But, by Joule's law, the heat-waste of the current whose strength is C running through resistance R, is expressed by the equation

$$= C^2 R \text{ (watts).}$$

Substituting this value above, we get

$$W = w + C^2 R.$$

Comparing equation [I] with equation [II] we get the following:—

$$\frac{w}{W} = \frac{E(V - E)}{V(V - E)};$$

or, finally,

$$\frac{w}{W} = \frac{E}{V}. \quad . \quad . \quad . \quad . \quad . \quad . \quad [\text{III}]$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its practical significance. We may appropriately call it *the law of Siemens.* Here the ratio $\frac{w}{W}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by so adjusting either the magnetism of the field-magnets or the speed of the motor that E is very nearly equal to V.

Now the power utilized is equal to the difference between the total power supplied and the part wasted in heat, or in symbols,

$$w = V\,C - C^2 R. \quad . \quad . \quad . \quad . \quad [\text{IV}]$$

In order to find[1] what value of C will give us the maximum value for w (which is the work done by the motor *in unit time*), we must take the differential coefficient and equate it to zero:

$$\frac{dw}{dC} = V - 2CR = 0,$$

whence we have

$$C = \frac{1}{2}\frac{V}{R}.$$

But, by Ohm's law, V/R is the value of the current when the motor stands still. So we see at once that, to get maximum work per second out of our motor, the motor must run at such a speed as to bring down the current to half the value which it would have if the motor were at rest. In fact, we here prove the law of Jacobi for the maximum rate of doing work But here, since

$$C = \frac{V - E}{R} = \frac{1}{2}\frac{V}{R},$$

it follows that

$$V - E = \frac{1}{2}V,$$

or

$$\frac{E}{V} = \frac{1}{2};$$

---

[1] The argument can be proven, though less simply, without the calculus, as follows: write equation [IV] in the following form:

$$C^2R - VC + w = 0.$$

Solving this as an ordinary quadratic equation, in which C is the unknown quantity, we have

$$C = \frac{V \pm \sqrt{V^2 - 4Rw}}{2R}.$$

To find from this what value of C corresponds to the greatest value of w, it may be remembered that a negative quantity cannot have a square root, and that therefore the greatest value that w can possibly have will occur when

$$4Rw = V^2,$$

for then the term under the root sign will vanish. When this condition is observed it will follow that

$$C = \frac{V}{2R},$$

or the current will be reduced to half its original value.

whence it follows also that

$$\frac{W}{w} = \frac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.[1]

GRAPHIC REPRESENTATION OF LAWS OF MOTORS.

Several graphic constructions have been suggested to convey these facts to the eye ; one of these enables us, in one diagram, to exhibit graphically both the law of maximum rate of working, and the law of efficiency.[2]

Let the vertical line, A B (Fig. 506), represent the electromotive-force V, of the electric supply. On A B construct a square A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive-force E of the motor. The length of this quantity will increase as the velocity of the motor increases. Let E attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows:— Through F draw F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive-force at work in the machine producing a current is V – E, which may be represented by any of the lines A F, K G, G H, or L C. Now the electric energy expended per second is V C; and since $C = \frac{V - E}{R}$, it may be written as

---

[1] It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Everyone is familiar with the rule for grouping a battery which consists *of a given number* of cells, that they will yield a maximum current through a given external resistance when so grouped, that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zinc of one's battery), is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in the heat of the cells, and half only will be available in the external circuit: If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will of course be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme case. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the armature part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy, the resistance of the armature should be very low as compared with that of the external circuit.

[2] See paper by the author in the *Philosophical Magazine*, Feb. 1883.

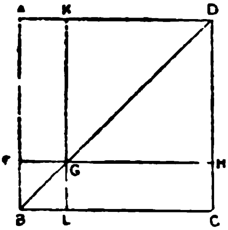


FIG. 506.

$$\frac{V (V - E)}{R};$$

and the electric energy utilized by the motor, measured in *watts*, is

$$\frac{E (V - E)}{R}.$$

R being a constant, the values of the two are proportional to

$$V (V - E) \text{ and } E (V - E).$$

Now the area of the rectangle

$$A F H D = V (V - E),$$

and that of the rectangle

$$G L C H = E (V - E).$$

The ratio of these two areas on the diagram is the efficiency of a perfect motor, under the condition of a given constant electromotive-force in the electric supply.

Turn to Fig. 507, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter electromotive-force E is very small compared with V. Here the area which represents the energy expended, is very large ; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

So far we have assumed that the efficiency of a motor (working with a given constant external electromotive-force) is to be measured electrically. But no motor actually converts into useful mechanical effect the whole of the electrical energy which it absorbs, since part of the energy is wasted in friction and part in wasteful electro-magnetic reactions between the stationary and moving parts of the motor. What we are expressing thus as useful work is the work actually delivered to the armature to drive it. It is mere matter of good engineering how small a percentage of this must be discounted for friction in the bearings, eddy-currents, hysteresis and the like. If, however, we might consider the motor to be a *perfect* engine (devoid of friction, not producing wasteful eddy-currents, running without sound, giving no sparks at the collecting-brushes, etc.), then we might take the mechanical output as being precisely equal to the actual power delivered electrically to the armature. Such a "perfect" electric engine would, like the ideal "perfect" heat engine of Carnot, be perfectly reversible. In Carnot's heat engine it is supposed that the whole of the heat actually absorbed in the cycle of operations is converted into useful work ; and in this case the efficiency is the ratio of the heat absorbed to the total heat expended. As is well known, this efficiency of the perfect heat engine can be expressed as a function of two absolute temperatures, namely those respectively of the heater and of the refrigerator of the engine. Carnot's engine is also ideally reversible ; that is to say, capable of reconverting mechanical work into heat.

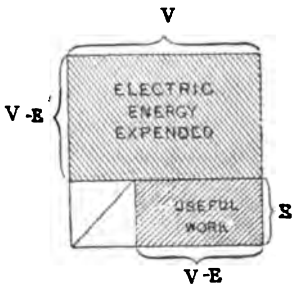


FIG. 507.

The mathematical law of efficiency of a perfect electric engine illustrated in the above construction is an equally ideal case ; and the efficiency can also be expressed, when the constants of the case are given, as a function of two electromotive-forces.

Law of Maximum Activity (Jacobi). Let us next consider the area G L C H of the diagram (Fig. 506), which represents the work utilized in the motor. The value of this area will vary with the position of the point G, and will be a maximum when G is midway between B and D ; for of all rectangles that can be inscribed in the triangle B C D, the square will have maximum area (Fig. 508). But if G is midway between B and D, the rectangle G L C H will be exactly half the area of the rectangle A F H D ; or, the useful work is equal to half the energy expended. When this is the case, the counter electromotive-force reduces the current to half the strength it would have if the motor were at rest ; which is Jacobi's law of the efficiency of a motor doing work at its greatest possible rate. Also F will be half-way between B and A, which signifies that E = ½ V.

Law of Maximum Efficiency.—Again, consider the two rectangles when the point G moves indefinitely near to D (Fig. 509). We know from common geometry that the rectangle G L C H is equal to the rectangle A F G K. The area (square) K F H D, which is the excess of A F H D over A F G K, represents therefore the electric energy which is

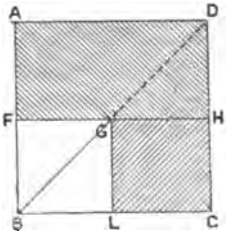


FIG. 508.—GEOMETRIC ILLUSTRATION OF JACOBI'S LAW OF MAXIMUM ACTIVITY.

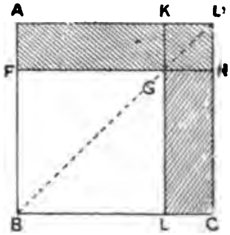


FIG. 509.—GEOMETRIC ILLUSTRATION OF THE LAW OF MAXIMUM EFFICIENCY.

wasted in heating the resistances of the motor. That the efficiency should be a maximum the heat-waste must be a minimum. In Fig. 507 this corner square, which stands for the heat-waste, was enormous. In Fig. 508 it was exactly half the energy. In Fig. 509 it is less than one-quarter. Clearly we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas G L C H and A F H D, which represents the efficiency, can therefore only become equal to unity when the square K G H D becomes indefinitely small—that is, when the motor runs so fast that its counter electromotive-force E differs from V by an indefinitely small quantity only.

It is also clear that if our diagram is to be drawn to represent any given efficiency (for example, an efficiency of 90 per cent.), then the point G must be taken so that area G L C H $= \frac{9}{10}$ area A F H D; or, G must be $\frac{9}{10}$ of the whole distance along from B towards D. This involves that E shall be equal to $\frac{9}{10}$ of V, or that the motor shall run so fast as to reduce the current to $\frac{1}{10}$ of what it would be if the motor were standing still. Thus we verify, geometrically, the law of maximum efficiency. If there is leakage in the line, then this law will require modification,[1] for the higher the counter electromotive-force of the motor, the higher will be the potential of the line and the greater the loss by leakage.

It is now evident what we have to do to obtain any desired percentage of efficiency. Suppose current is supplied at 100 volts at the mains: then to utilize 90 per cent. we must employ as motor a dynamo which, when running at its proper speed and output, generates an electromotive-force of 90 volts.

We may now extend the graphic method to a further case.

Suppose that V is no longer taken as a constant, but that the work to be done by the motor per second is a constant. For this case we may write equation [II], p. 801, as

$$E\,(V - E) = w\,R.$$

---

[1] See Kapp's *Electric Transmission of Energy*, 4th edition, p. 185.

This equation is graphically represented by the curve P H Q (Fig. 510), in which the values of V are plotted as abscissæ and those of E as ordinates. From this curve it is at once seen that there will be a certain minimum value of V which will suffice to give to the motor the prescribed amount of energy per second. The curve is so drawn that it passes through the corner H of all the areas equal to G L C H drawn to fit under the diagonal of the square. Of these areas, which represent equal work done by the motor, the one which has minimum value of V is the square which fits to the apex of the curve and corresponds to the case where V = 2 E. This result, which was first pointed out by Prof. Carhart,[1] is the converse of Jacobi's law, and, like it, involves an efficiency of only 50 per cent. A much higher efficency is obtained when V and E are both greater, as indicated by the square drawn through the point *h*.

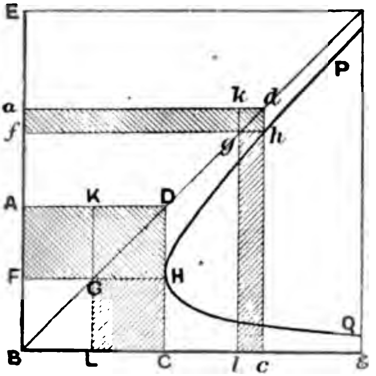


FIG. 510.

SPEED AND TORQUE OF MOTORS.

Certain very important relations subsist between the condition of the electric supply and the speed and turning-moment of a motor.

In Chapter IX., on Actions and Reactions, it was set forth that the power transmitted along a shaft is the product of two factors, the speed and the torque. If ω stands for the angular velocity and T for the torque,[2] then

$$\omega T = \text{mechanical work per second, or power.}$$

---

[1] *American Journal of Science*, xxxi. 95, 1886.

[2] If n be the number of revolutions per *second*, then $2\pi n = \omega$. Also if F be the transmitted pull on the belt (or rather the difference between the pull in that part of the belt which is approaching the driving pulley and the pull in that part which is receding from the driving pulley) in pounds weight, and r be the radius of the pulley, $F r$ = the turning-moment or torque = T, then $\omega T = 2\pi n r F$ = the number of foot-pounds per second transmitted by the belt. This may also be proved as follows: Horse-power is product of the force into the velocity. The

This may be expressed in watts by use of the proper coefficient.

Now, if E is the electromotive-force generated by the armature, and C the current through it, the electric energy per second in the armature is[1] the product—

$$E\,C = \text{electric work per second (in watts).}$$

If the whole of these four quantities, ω, T, E and C, are armature quantities, strictly, we may equate the electrical and mechanical expressions together; and the equation will be true for either a motor or a generator. In the generator, E and C are in the same direction and T opposes ω; or there is a counter-torque. In the motor, T and ω are in the same direction, but E opposes C; or there is a counter electromotive-force.

In treating of the dynamo as a generator, it was assumed that the mechanical power could be supplied under one of the two standard conditions, on the one hand of *constant speed* (and torque varying with the electrical output), or else on the other of *constant torque* (and speed varying with the output). One of these two mechanical conditions being prescribed, algebraic expressions had then to be found for the two corresponding factors of the electric output, namely, the *electromotive-force* and the *current*, under varying conditions of resistance in the circuit. Also we investigated those conditions which would result in making one or other factor of the electric

---

circumference of the pulley is $2\pi r$, and it turns n times per second, therefore the circumferential velocity is $2\pi r n$, and this, multiplied by F, gives the work per second. If F is expressed in grammes weight, and r in centimetres, then $2\pi r n\,F$ will give the power in gramme-centimetres, and must be divided by $7{\cdot}6 \times 10^6$ to bring it to horse-power, and must be multiplied by 981×10^{-7} to bring it to watts. If ω is in radians per second and T in dyne-centimetres, then the product will be in ergs per second, and can be brought to watts by dividing by 10^7. It is convenient also to remember that the British unit of torque, one *pound-foot* (i.e. the turning effort of a force equal to the weight, at London, of one pound acting with a leverage of one foot) is equivalent to $1{\cdot}356 \times 10^7$ dyne-centimetres.

[1] Since 1 volt = 10^8 C.G.S. units of electromotive-force, and 1 ampere = 10^{-1} C.G.S. units of current, 1 watt (or volt-ampere) will be = 10^7 C.G.S. units of work per second = 10^7 ergs per second = $10^7 \div 981$ gramme-centimetres per second.

output constant. It was found convenient to study the relation between the two factors of output by the aid of the curves known as *characteristics.*

Similarly, in treating the dynamo as a motor, it will be assumed that such arrangements of electric supply can be made that the electric power can be furnished under one of the two standard conditions, on the one hand of *constant potential* (and current varying with the mechanical output of the motor), or on the other of *constant current* (and potential varying with the mechanical output). One of these two conditions being prescribed, we shall then have to find algebraic expressions for the two corresponding factors of the mechanical output, namely, the *speed* and the *torque*, under varying conditions of load on the shaft. Also, we shall investigate what are the conditions which will result in making one or other factor of the mechanical output constant: in other words, we shall ascertain what are the conditions of self-regulation to make the motor run at constant speed or with constant torque. Lastly, it will be found convenient to study the relation between speed and torque by the aid of curves, which, by analogy we may call *mechanical characteristics.*

GENERAL EXPRESSIONS FOR TORQUE AND SPEED.

The power imparted to the shaft of a motor may be expressed either in electrical or mechanical measure, and in either case may be stated in *watts.* Electrically it is the product of the motor's electromotive-force (i.e. the counter electromotive-force generated in its armature) into the current flowing in the armature. Mechanically it is the horse-power multiplied by 746. But, mechanically it is also proportional to the product of angular speed and torque. If the torque be expressed in terms of the pound-foot[1] as the unit, and if T stand for this torque in pound-feet, and if n be the number of revolutions per second, then, $2\pi n \mathrm{T}$ will be the power expressed in foot-pounds per second. Dividing by 550 will bring this to horse-power, whence the power in watts may be stated as :—

---

[1] One *pound-foot* is the turning moment exerted by a force equal to the weight of one pound if acting with a leverage of one foot.

$$w = 2\pi n \mathrm{T} \times \frac{746}{550} = 8 \cdot 52 n \mathrm{T} ; \quad . \quad . \quad [1]$$

or, electrically

$$w = \mathrm{E}\,\mathrm{C}_a \quad . \quad . \quad . \quad . \quad . \quad . \quad [2]$$

Now E the electromotive force generated by the armature is $= n \mathrm{Z} \mathrm{N} \div 10^8$, exactly as in a dynamo, if the armature is parallel-wound; or, if the armature is series-parallel wound (p. 366) the value of E will be $= \frac{p}{c} n \mathrm{Z} \mathrm{N} \div 10^8$; where p is the number of poles, and c the number of circuits through the armature. To simplify the expressions that follow, let us write M for the group of symbols $\frac{p}{c} \mathrm{Z} \mathrm{N} \div 10^8$; where therefore M will have as its physical meaning the volts generated by the armature if the speed were reduced to one revolution per second. Then we may at once write

$$\mathrm{E} = n \mathrm{M} ;$$

and

$$w = n \mathrm{M} \times \mathrm{C}_a \quad . \quad . \quad . \quad . \quad . \quad . \quad [3]$$

equating [1] and [3] we have :—

$$8 \cdot 52 n \mathrm{T} = n \mathrm{M}\,\mathrm{C}_a ,$$

whence

$$\mathrm{T} \text{ (in pound-feet)} = 0 \cdot 1175 \mathrm{M}\,\mathrm{C}_a \quad . \quad . \quad [4]$$

This is *the fundamental formula for all motors.*

The quantity M which appears in it, is, as defined above, the voltage it generates at unit speed, and is proportional to the magnetic flux per pole and to the number of armature conductors per circuit. M being also proportional to the torque per ampere we may call it the *effort-factor.* It now appears that the torque of the motor, if the magnetism is constant, is proportional simply to the armature current and independent of the speed.

Examples :

I. *Westinghouse 4-pole Tramway Motor.* $Z = 760$; $N = 4{\cdot}16 \times 10^6$; $p = 4$; $c = 2$: whence $M = 63{\cdot}28$; therefore, when $C_a = 70$ amperes, it follows that $T = 510$ pound-feet.

II. A two-circuit 4-pole motor is required such that it shall exert on its shaft a full-load torque of 200 pound-feet, shall run at 525 revolutions per minute, when at a normal full-load of 20 H.P., and shall work at 500 volts. Assuming it to be shunt-wound, and that the internal voltage drop is 10 volts, find C_a and M. $C_a = 20 \times 746 \div 490 = 30{\cdot}4$ amperes; $M = 400 \div (0{\cdot}1175 \times 2 \times 30{\cdot}4) = 56$.

III. Find the torque exerted by a "G.E. 52" motor taking 51 amperes at 500 volts, the armature running at 640 revolutions per minute. Here $V = 500$; $n = 10\frac{2}{3}$; whence $M = 46{\cdot}9$. Hence by formula [4] $T = 0{\cdot}1175 \times 46{\cdot}9 \times 51 = 239$ pound-feet.

IV. A motor required to work on 200-volt mains is of such design that it shall start under a dead load equivalent to a torque of 180 pound-feet, and not take more than 20 amperes at starting; further, that at no-load it shall not run at a higher speed than 180 revolutions per minute. Find M, n, N, and Z. By formula [IV], $M = 180 \div (0{\cdot}1175 \times 20) = 76{\cdot}68$. And $V \div M = n = 200 \div 76{\cdot}68 = 2{\cdot}62$. Hence, there will be $2{\cdot}62 \times 60 = 157{\cdot}2$ revolutions per minute.

To develop further the expression for the torque, we may remember that C_a can be calculated in terms of the electromotive-force of supply V, as measured at the terminals of the motor, and the internal resistance, which we call r; and then

$$C_a = \frac{V - E}{r};$$

whence it follows that

$$T = 0{\cdot}1175 \times M \frac{V - nM}{r} \quad . \quad . \quad . \quad [5]$$

If in this formula M is assumed constant, it follows that if the speed rises so high that $nM = V$, there will be no torque. In fact, when the motor runs without any load it runs up to its top speed which is $= V \div M$.

On the other hand, the greatest value of the torque is when the speed is zero, being then equal to $0 \cdot 1175 \times \mathrm{M\,V}/r$; the current being at its maximum. If the resisting torque be greater than this maximum value of the motor's torque, it cannot start.

An expression for the speed of the motor is obtained from [5] by simple transformation:—

$$n \text{ (revs. per sec.)} = \frac{\mathrm{V}}{\mathrm{M}} - \frac{8 \cdot 52\, r\, \mathrm{T}}{\mathrm{M}^2} \quad . \quad . \quad [6]$$

The relation between n and T may be plotted as a *mechanical characteristic* of the motor. If the magnetism is constant at all loads, then this characteristic (Fig. 511) will be a straight line

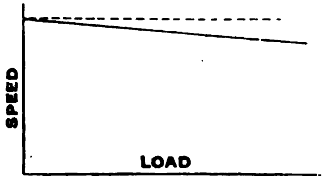


Fig. 511.—Mechanical Characteristic of Motor with Constant Magnetism, working on Constant Voltage.

sloping down as the load increases: the drop in speed being proportional to the load and to the internal electric resistance of the motor. The effect on the characteristic of the variation of the magnetism in the cases of series-wound or shunt-wound motors is studied later.

Gear-Ratio.—If the motor is geared down so that its armature revolves g times faster than the driven shaft, the torque on the latter will (apart from the frictional loss in the gearing) be g times greater than that of the motor armature.

Example.—In the G.E. motor quoted above the armature pinion had 14 teeth, the axle gear-wheel 67, making the gear-ratio 4·78. As the torque on the motor was 239 pound-feet, that on the driving axle was 1141·4 pound-feet.

Draw-Bar pull.—The pull exerted by a locomotive motor geared to driving wheels on rails or on the ground depends on (*a*) the torque of the motor, (*b*) the gear-ratio, (*c*) the size of the driving-wheel. Let P stand for the draw-bar pull in *pounds'* weight; D_w the diameter of the driving-wheel in *feet.* Then the torque of the motor being T, and that of the driving-wheel gT, it follows that $gT = \frac{1}{2}D_w P$; whence the rule for the draw-bar pull:—

$$P = \frac{2gT}{D_w}; \quad . \quad . \quad . \quad . \quad . \quad . \quad [7]$$

which may also be written:—

$$P = \frac{0{\cdot}235\, g M C_a}{D_w}, \quad . \quad . \quad . \quad . \quad . \quad [8]$$

or as

$$P = 0{\cdot}235 \frac{gM}{D_w} \cdot \frac{V - nM}{r} \quad . \quad . \quad . \quad [9]$$

Example.—Find the draw-bar pull of the G.E. motor, having driving-wheels 33 inches in diameter. Here D_w is $33 \div 12 = 2{\cdot}75$ feet. Therefore by formula [7] P = 830 pounds' weight. The actual draw-bar pull at this current (51 amperes) was found to be 770. owing to the reduction of M by armature reaction.

The three equations [1] to [6] above are true, not only for motors, but for generators. Equation [5] will give negative values for T, the significance of the sign being that the torque due to the action of the magnetic field on the conductors carrying the armature current is such as to oppose the driving.

If r is very small, and M relatively very large, the second term in [6] may be neglected, and the speed will then depend on the first term only. It will be the smaller as M is greater: this being the simple converse of the corresponding fact that the more powerful the magnetic field the less need be the speed of the dynamo to give the desired output. We may also notice that if M is constant, the speed is proportional to V: it will be constant if the condition of supply is that of constant potential, but will be variable if V varies.

We must next inquire how n and T are affected by the fact that the value of N and therefore of M depends upon the construction and winding of the field-magnet of the motor, and by the conditions of supply. We shall consider the following kinds of machine:—

A. *Magneto Motor* and *Separately-excited Motor.*
B. *Series-wound Motor.*
C. *Shunt-wound Motor.*
D. *Compound-wound Motor.*

In each instance we shall have to take into account the conditions of supply, according as V or C is constant.

MAGNETO MOTOR AND SEPARATELY-EXCITED MOTOR.

It is here assumed that N is constant; in other words, that the perturbing reactions of the armature may be neglected. Under these circumstances the general formulæ already found require small modification. The only internal resistance is that of the armature r_a.

Case (i.): V *constant.*

In this case formula [6] gives the desired relation, from which the *mechanical characteristic* may be plotted out, as in

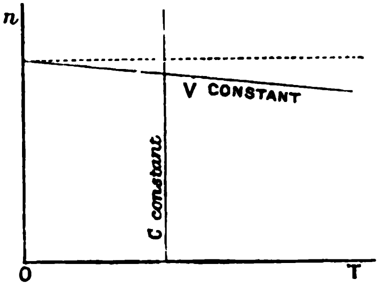


FIG. 512.—MECHANICAL CHARACTERISTICS OF MAGNETO MOTOR.

Fig. 512. It is a straight line cutting the axis of n at a point representing to scale that speed at which $n\,\mathrm{M} = \mathrm{V}$; and it slopes downwards at an angle such that the tangent of the slope is equal to $2\,\pi\, r_a \div \mathrm{M}^2$, or is proportional to the internal resistance. In the case of the separately excited motor, increase in the exciting current, strengthening the field, will obviously

make the sloping line more nearly horizontal, as well as lowering the speed as a whole.

If we attempt to take into account the reactions of the armature, we must remember that the effect of the armature current is to demagnetize, if there is a backward lead, and to magnetize if there is a forward lead. A backward lead, then, would tend to make the sloping line, at constant V, rise and become more level as the torque increased, because it would weaken the magnet, and so let the speed increase; whilst a forward lead would tend to make it slope still more.

Case (ii.): C *constant.*

In this case, as reference to formula [4] shows, the torque is constant, being independent of speed and of internal resistance. The mechanical characteristic of the machine under these conditions is a vertical straight line.

SERIES MOTOR.

The fundamental equations are as before, with the addition of the following:—

$$r = r_a + r_m;$$

but now we may with advantage introduce the approximate formula for the law of the electromagnet given in Chapter IV., and write, as on page 114, where C′ is the diacritical current and $h = S\,C'$,

$$N = \bar{N}\frac{C}{C + C'};$$

whence, if Z is fixed, it follows that

$$M = \bar{M}\frac{C}{C + C'}.$$

Putting this value into the expression [4], on page 811, for the torque, and writing for brevity $0 \cdot 1175\,\bar{M} = Y$, we have

$$T = Y\frac{C^2}{C + C'}. \quad . \quad . \quad . \quad . \quad [10]$$

This relation between torque and current is given graphically in Fig. 513. For values of C that are small as compared with C', T varies nearly as C^2; whilst for large values of C, as magnetic saturation advances, T is nearly proportional to C. The equation may also be written in the quadratic form—

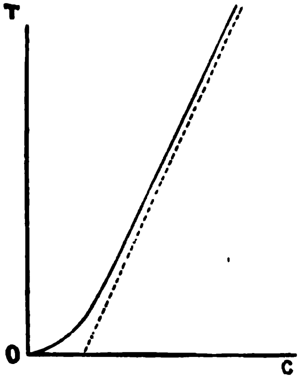


FIG. 513.—TORQUE CURVE OF SERIES-MOTOR.

$$C^2 - \frac{T}{Y} C - \frac{T}{Y} C' = 0,$$

the solution of which is

$$C = \frac{T}{2Y}\left\{1 \pm \sqrt{1 + \frac{4Y}{T} C'}\right\}.$$

It is permissible for large values of T to neglect the second term under the root sign, since the magnetization grows nearly constant.

As an example plot the following figures taken from a test of a 30 H.P. street-car motor, where the torque is given in pound-feet, the current in amperes, and the speed in revolutions per minute:

Current	3·5	10	20	30	40	50	70	90	94
Torque	0	29	95	183	281	385	610	863	912
Speed ..	479	236	145	118	99	85	61	39	35

Now from [4] and [6] above we may eliminate M, giving

$$n = 0{\cdot}1175\left\{\frac{VC}{T} - \frac{rC^2}{T}\right\};$$

and inserting the value of T from [10] we get

$$n = 0{\cdot}1175 \left\{ \frac{V}{Y} \cdot \frac{C + C'}{C} - \frac{r}{Y} \cdot C + C' \right\} ;$$

from which the characteristic (Fig. 514) may be plotted.

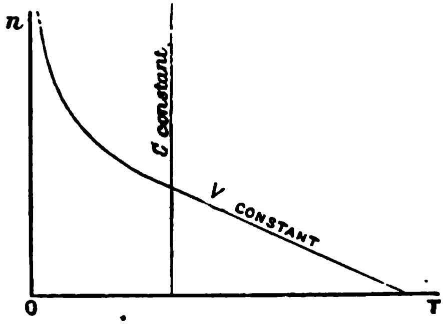


FIG. 514.—MECHANICAL CHARACTERISTICS OF SERIES-MOTOR.

Case (i.) : V *constant.*

If V is constant, then if T is large, C will also be large relatively to C′, and the equation becomes

$$n = \frac{0{\cdot}1175}{Y} (V - rC),$$

which corresponds to the last part of the mechanical characteristic, which is nearly a straight line when the magnets are well saturated.

Case (ii.) : C *constant.*

Here, clearly, saving for armature reactions, the magnetization will be constant ; hence the torque will also be constant, as in Fig. 514. With a load exceeding a certain amount, the motor will not start ; with a lesser load it will race until friction and eddy-currents make up the difference.

The properties of series-wound motors are so important that we may pause to consider them a little more fully. We know that if the current running through a series dynamo be constant, so that its magnetism is constant, the electromotive-force it develops is almost exactly proportional to its speed. It therefore follows that if E is proportional to n, T will be proportional to C. This is abundantly verified in the case of series motors by experiments. When a Siemens series dynamo was arranged to lift a load of 56 lb. on a hoist, it lifted this load at the rate of 212 feet per minute, developing a counter electromotive-force of 108·81 volts. The applied electromotive-force was 111 volts, and the resistance of the circuit was 0·3 ohm. The effective electromotive-force was therefore 2·19 volts and the current 7·3 amperes. When the resistance of the circuit was increased to 2·2 ohms, the speed fell to 169 feet per minute, the counter electromotive-force to 94·94; the effective electromotive-force V – E, was therefore 16·06 volts, and the current 7·3 amperes as before. When 4·8 ohms were inserted, the speed fell to 141 feet per minute, and E to 76 volts; V – E was 35 volts, and the current 7·3 amperes as before. *With the same load, the same current,* whatever the speed.

Advantages of Series Motors.—If the magnetism of the field is strengthened, the torque for a given current in the armature increases proportionally. Hence in series-motors there is a great advantage at starting. For at starting, when because the armature is not exercising any back electromotive-force there is a large current through the armature, the field-magnet also receives a great accession of magnetism. Hence the starting torque may far exceed the normal full-load torque. The fact that the torque of a series motor is thus dependent on the current is of advantage in the application of motors to propulsion of vehicles (such as tram-cars) which at starting require for a few seconds an effort greatly in excess of that needed when running.[1]

In the series motor, when supplied at constant potential, E is not proportional to the speed, because the field-magnetism is not constant, but falls off as E increases, being (if unsaturated) nearly proportional to $\dot{V} - E$. It therefore will not run at a constant speed. Neither will it run at a constant speed if supplied with a constant current.

---

[1] See remarks by E. Hopkinson, *Proc. Inst. Civil Engineers,* xci. pt. i. 6, 1887.

Fig. 515 gives the tests of a series motor of the Electricity and Hydraulic Company, of Charleroi. The draw-bar pull, in pounds' weight is proportional to the torque.

Use of two Series Machines in Transmission.—If two similarly-constructed series-wound machines are used—one as generator, the other as motor—the arrangement is almost perfectly self-regulating, the speed of the motor at the receiving end being almost constant if that of the dynamo at the transmitting end is constant. Every addition to the load put upon the motor, tending to check the speed, causes an increase of current to flow, and so throws proportionate additional work upon the generator, which in turn takes more power from the

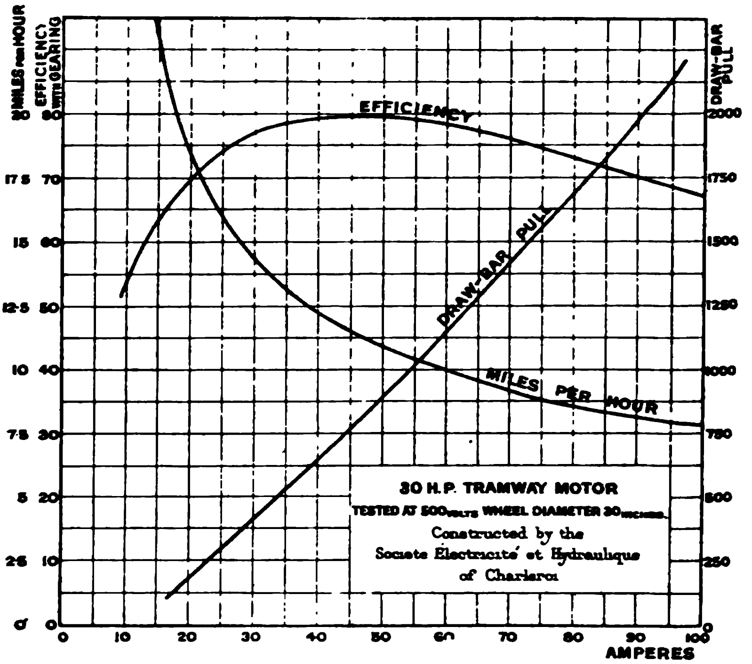


Fig. 515.—Tests of Tramway Motor.

steam engine to keep up its speed. As we have shown above, the torque of the motor T_2 will depend, in the given machine, on the current alone, and on the current will depend the torque at the dynamo T_1. Mr. Kapp has further shown[1] how, if there is a resistance in the line, the arrangement may still be made self-regulating by choosing as generator and motor two machines so wound that comparing their characteristics for the prescribed speeds, the difference in their electromotive-forces corresponding to a given value of current shall be equal to the electromotive-force requisite to drive that particular current through the resistance in the whole circuit.

Use of two Series Motors in Series or Parallel Grouping.—Reference is made later to the combination of two similar motors with a switch that will group them in series at starting and in parallel after a certain speed has been attained. Putting the machines in series at starting is equivalent to halving the voltage on each machine; therefore reduces the rush of current at starting without requiring so much waste of power by resistance.

SHUNT MOTORS.

The fundamental conditions are as follows :—

$$T = 0{\cdot}1175\ M\ C_a,$$
$$C_a = C - C_{sh};$$

and, adopting the appropriate form (see p. 114) for the law of magnetization, where V′ represents the half saturating volts ;

$$N = \bar{N}\frac{V}{V + V'};$$
$$E = V\left(1 + \frac{r_a}{r_{sh}}\right) - r_a C.$$

From the first three of these we get

$$T = 0{\cdot}1175\ M\left(C - \frac{V}{r_{sh}}\right)\frac{V}{V + V'};$$

---

[1] See Kapp's *Electrical Transmission of Energy*, 4th edition, p. 199

and, transposing and writing Y as before for $0{\cdot}1175\ \mathrm{M}$;

$$\mathrm{C} = \frac{\mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathrm{V}+\mathrm{V}'}{\mathrm{V}} + \frac{\mathrm{V}}{r_{sh}};$$

and from the last of the four

$$n = \frac{1}{\mathrm{M}}\left\{\mathrm{V}\left(1 + \frac{r_a}{r_{sh}}\right) - r_a\mathrm{C}\right\}.$$

Inserting the value of C, we have

$$n = \frac{\mathrm{V}}{\mathrm{M}}\left\{1 - \frac{r_a\mathrm{T}}{\mathrm{Y}} \cdot \frac{\mathrm{V}+\mathrm{V}'}{\mathrm{V}^2}\right\}.$$

Case (1); V *constant.*

The last equation shows that a shunt-motor, supplied at constant potential, will have a speed that would be constant and independent of the torque if it were not for internal resistance; and further, that the consequent drop in speed as the torque increases will be the less as the field-magnetism is the more powerful.

As an example, a Victoria shunt motor tested by Mr. Mordey, in which the load was varied from $91{\cdot}8 \times 10^7$ to $1357{\cdot}2 \times 10^7$ dyne-centimetres, only decreased its speed from $16{\cdot}25$ to $15{\cdot}75$ revolutions per second.

It is instructive to contrast the self-regulating power of a shunt dynamo with the self-governing power of a shunt motor. The former, when driven at a constant speed, generates electric power at a nearly constant potential; the latter, when supplied from the mains at a constant potential, would furnish mechanical power at a nearly constant speed; and in both cases the departure from absolute constancy is proportional to the internal resistance of the armature coils, and to the output electrical or mechanical, of the machine for the time being.

So far we have supposed the armature to exert no magnetic reaction. Now, as we shall see, to obtain sparkless running there must be[1] a backward lead, and in motors a backward lead tends to demagnetize. But demagnetizing tends, as we have seen, to increase the speed; hence in the case of constant pressure supply, when there is a great load, the very reaction of the great current will tend to prevent the speed from falling, making the shunt motor very nearly self-regulating. These reactions must now be considered in detail.

---

[1] This is true if copper brushes are used; but with carbon brushes modern motors will run sparklessly with zero lead.

Case (ii): C *constant.*

The determination of this case is more complicated, though the general considerations are simple enough. If the motor is standing still when the current is turned on, nearly all the current will go through the armature, next to none through the shunt; hence there will be little magnetism, and therefore almost no torque. Such a machine will not start itself with any load on; but if it be once started, its counter electromotive-force will cause the current in the armature to decrease, whilst that round the shunt increases. The torque will therefore then increase with the speed, but not indefinitely, for as the magnetism advances in its degree of saturation, the increase of N will no longer compensate for the decrease of C_a; and from that point onwards the torque will decrease if the speed is allowed to increase. And, hypothetically, the speed should increase until the motor's own electromotive-force exactly equals the difference of potentials due to the whole of the constant current flowing through the resistance of the shunt, under which circumstances there will be no current through the armature and zero torque. Fig. 516, which, like the preceding, is taken from Dr. Frölich's work, gives the mechanical characteristics for the two cases.

Regenerative Control.—Sir C. W. Siemens[1] drew attention in 1880 to the singular properties of the combination of a generating dynamo and an electric motor, instancing a locomotive motor which, when descending an incline, quickens its speed and actually becomes a generator of currents, paying back the spare power into store. He also remarked how two trains driven by motors running on the same system of lines, tend to regulate one another, the one on a descending portion of the road transmitting power to the other, as though "connected by means of an invisible rope." With separately excited motors and shunt-motors this is so: for at a definite speed the shunt motor becomes a generator, its magnetism being almost invariable. But in the case of series-wound motors, since the increase of speed down-hill decreases the current, it decreases also the magnetism of the field-magnets, and there is no definite speed at which such a motor becomes a generator.

---

[1] *Journal Soc. Telegr. Engineers*, ix. 301, 1880.

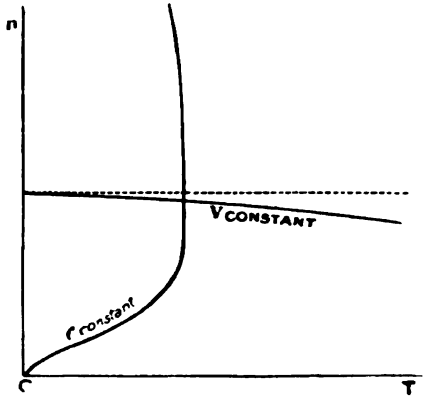


FIG. 516.—MECHANICAL CHARACTERISTICS OF SHUNT MOTOR.

REACTION BETWEEN ARMATURE AND FIELD-MAGNETS IN A MOTOR.

On pp. 208 to 216 and 250 to 255, the reactions between the armature and field-magnets of a dynamo were considered in detail, but attention was confined solely to that which occurs when the dynamo is used as a generator. In that case we noted that the current in the armature tended to cross-magnetize the armature core and to distort the field in the sense of the rotation; while the forward lead of the brushes, needful for sparkless commutation of the current, tended to exercise a demagnetizing effect. The same thing is true of a motor; but with a difference. A current supplied from an external source magnetizes the armature and makes it into a powerful magnet, whose poles would lie, as in the bipolar dynamo, nearly at right angles to the line joining the pole-pieces, were it not for the fact that in this case also a lead has to be given to the brushes. Suppose, as in so many of the drawings in this book, that the S-pole of the field-magnets is on the left, and the N-pole on the right. Also that the current so traverses the armature that it causes the highest point to be a S-pole and the lowest point a N-pole. This means that if the armature is wound right-handedly the current must come in through the top brush and leave by the bottom one, the top brush being connected to the + main. Compare with page 209. Clearly, in this case, the armature will rotate right-handedly, because the S-pole at the top will be repelled from the S-pole on the left and attracted toward the N-pole on the right. It will therefore run right-handedly (in a right-hand field) when the current flows downwards from top to bottom, exactly as the armature of a generator must run in order to send a current upwards. In each case the direction of the induced electromotive-force is the same—upwards—*with* the current in the generator, *against* the current in the motor.

It follows that in a motor a *forward* lead would convert the cross-magnetizing force into one that tends to increase that of the field-magnet, whilst a *backward* lead tends to demagnetize. Further, since with a forward lead the armature polarity strengthens that of the field-magnet, it is possible (apart from the question of sparking) for a motor to be worked without any other means being taken to magnetize the field-magnets (see p. 259): the armature will induce a pole in the field-magnet and then attract itself round towards this induced pole. This principle has been used for many years in small motors.

The cross-magnetizing force will also have the effect of weakening the field under the two forward pole-tips, and of strengthening them under the two hindward pole-tips. This is the opposite effect to that in a dynamo. In the motor (without lead even) the cross-magnetizing reaction tends to shift round the field in a sense *opposite* to that of the rotation. We shall now see what are the conditions for minimum sparking. Consider (Fig. 517) a coil W ascending on the left. The current in it is descending from the top brush, whilst it is itself the seat of an electromotive-force that tends to stop or reverse its current. Now we know that on the theory of the reversing field the condition of non-sparking requires that at the moment whilst the coil passes under the brush, and is short-circuited, it should be passing through a field that is not only sufficiently strong, but one that tends to reverse the direction of its current. It is already in such a field; hence the act of commutation must take place *before* it passes out of this magnetic field. It must be commuted before it arrives at the highest point. In other words, a backward displacement must be given to the brushes if there is to be no sparking. The neutral line *n n'* will therefore rake *backwards* in a motor into the fringe of the magnetic field. But since (in every case) both eddy-currents and

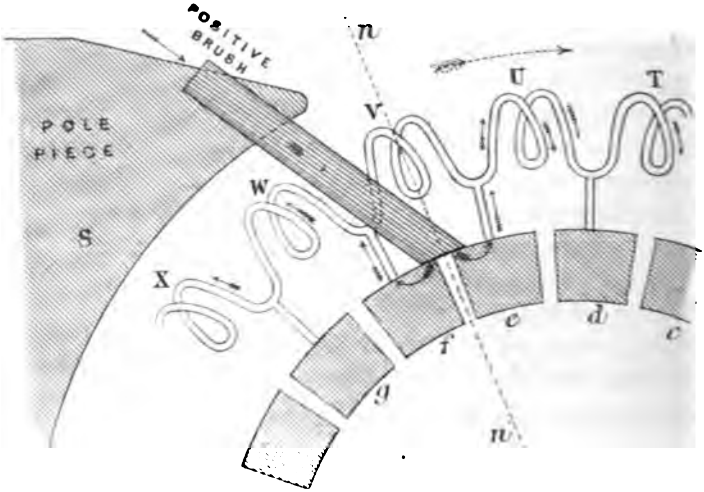


FIG. 517.—THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A MOTOR.

hysteresis tend to shift the magnetic field slightly in the direction of the rotation—increasing the lead in a generator, diminishing it in a motor—it follows that the negative (or backward) lead in a motor may be slightly less than the positive (or forward) lead in a generator, for equal flow of current and equal excitation.[1] The advantage in point of weight of a motor in which the armature should help to excite the field-magnets, thereby reducing the weight of the latter, led Professors Ayrton and Perry,[2] in 1883, to advocate designs with weak field-magnets and powerful armatures acting with a forward lead. But from the foregoing considerations it follows that if a forward lead is given to the brushes of a motor in order to get a more powerful rotation, the motor will spark at the brushes. With carbon brushes covering several segments, it is not necessary to give any lead either forward or backward, the contact resistance at the brushes acting as explained on p. 251 to effect commutation without sparking. Carbon brushes are almost always used for motors, as their position end-on is suitable for revolution in either sense. The resistance of the film between the commutator and the brush is here the principal agent in the sparkless commutation.

Minimum of sparking may be reconciled with high efficiency by following out the very same principles of design and construction which were found to be correct guides in the case of dynamos used as generators (p. 255). Mr. Sayers, whose method of winding armatures with auxiliary commuting coils was considered on p. 270, has applied the same method[3] to the armatures of motors. With this device the current flows through the armature sparklessly even though a considerable forward lead is given to the brushes; and in this way the armature is able to help the magnetization of the field-magnets.

---

[1] This appears to be the explanation of the differences—otherwise unimportant—observed by Snell; *Journal Inst. Electr. Engineers*, xix. 194, 1890.

[2] *Journal Soc. Telegr. Engineers*, xii. May 1883.

[3] *Inst. Electr. Engineers*, xxii. 377, 1893; xxiv., 1895.

As a rule, a machine used as a motor will carry a higher current without sparking than it will carry if used as a generator. Also, a motor when starting will carry without sparking an overload of current quite twice as great as it would carry as a generator. The simple explanation is that in this case the *time* within which the commutation takes place is so much greater.

Comparison of Dynamos and Motors.—Mr. Mordey,[1] who has carefully tracked out the analogies between dynamos and motors, has observed that in several respects it is even more important that the rules laid down for the good design of generators should be observed for motors. Eddy-currents must be even more carefully eliminated.

Contrast the conditions which are bound up in the disposition of the magnetic fields of the generator and the motor respectively. In one the armature is mechanically driven round while the magnetic forces in the field tend to pull it back. In the other, the magnetic forces of the field tend to drag it round, and it is thereby enabled to do mechanical work. In one case there is an opposing mechanical reaction tending to stop the steam engine. In the other there is set up an opposing electrical reaction (the induced counter electromotive-force) tending to stop the current.[2] In both cases the rotation is supposed to be taking place in the same sense—right-handedly. In both the effect is to displace the lines of force of the field, but in the generator the mechanical rotation acts as if it dragged the magnetism round, whilst in the motor the reciprocal magnetic reactions act as if they tried to drag round the armature, producing mechanical rotation. In the normal types of generator we found sparkless reversal to require a positive lead. In the motor, on the contrary, sparkless reversal would necessitate a negative lead. If a motor is set with no lead, and if the field-magnets are very weak or are not excited at all, it will run in either direction according as it may be started. If in a motor with well-excited field-magnet the current be reversed in the *armature part* of the circuit only, the motor will usually reverse its rotation, but will usually require the lead to be reversed also, if it is to run as sparklessly as before. If, instead of reversing the current in the armature, the magnetism of the field-magnet be reversed, a similar result will follow. If both are reversed at the same time, the motor will go on rotating as if nothing had happened.

---

[1] *Phil. Mag.*, Jan. 1896.

[2] The law of the electrical reaction resulting in a generator from the mechanical motion is summed up in the well-known law of Lenz, that *the induced current is always such that by virtue of its electro-magnetic effect it tends to stop the motion that generated it.* In the converse case of the mechanical reaction resulting, in a motor, from the flow of electric energy, it is easy to formulate a converse-law, viz. that *the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current.*

Dynamos wound and connected for working as generators of continuous currents may be used in all cases as motors, but with some difference. A series dynamo set to generate currents when run right-handedly (and therefore having a forward right-handed lead), will, when supplied with a current from an external source, run as a motor, but runs left-handedly against its brushes. To set it right for motor purposes requires *either* that the connexions of the armature should be reversed, *or* that those of the field-magnet should be reversed (in either of which cases it will run right-handedly), *or* else the brushes must be reversed and given a lead in the other direction (in which case it will run left-handedly). A shunt-dynamo set ready to work as a generator will, when supplied with current, run as a motor in the same direction as it ran as a generator; for if the current in the armature part is in the same direction as before, that in the shunt is reversed, and *vice versa.* A compound-wound dynamo, set right to run as a generator, will run as a motor in the reverse sense, against its brushes if the series part be more powerful than the shunt, and with its brushes if the shunt part be the more powerful. If the connexions are such (as in compound dynamos) that the field-magnet receives the sum of the effects of the shunt and series windings when used as a generator, then it will receive the difference between them when used as a motor. There are certain advantages in using a differentially-wound motor, as will appear hereafter.

REVERSING GEAR FOR MOTORS.—A motor, as will be seen from the preceding discussion, can be reversed by the operation of reversing the current through the armature, and at the same moment reversing the lead. But reversing the current can also be accomplished by rotating the brushes through 180°. Consequently both these actions may be accomplished by the single operation of advancing the brushes through $180° - 2\phi$, where ϕ is the original angle of lead. But as the brush would then slant in the wrong direction, it is usual to provide a second set of brushes. This is, indeed, Hopkinson's method of reversing. He employed two pairs of brushes, each pair being capable of moving about a common pivot, so that either the pair having a lead in one direction, or the pair having a lead in the other direction can be let down upon the commutator. Various other forms of reversing gear have been proposed to accomplish the desired end. If the field-magnets of a motor are so powerful relatively to the armature that no lead has to be given to the brushes, the rotation can be reversed by simply reversing the current through the armature.

GOVERNMENT OF MOTORS.

For many purposes, as in driving textile machinery, it is extremely important that motors should be so governed as to run at a uniform speed, no matter what the load. Centrifugal governors, interruptor governors, and dynamometric governors have all been suggested.[1] Series-wound machines are not suitable for this work. Shunt-wound machines are, as mentioned above, fairly self-regulating if supplied at constant voltage. Mordey[2] has pointed out its dependence on good design and low armature resistance. The slight demagnetizing action of the armature when a negative non-sparking lead is given to the brushes, acts, in fact, instead of any special demagnetizing coil. The following tests showed a constancy to within 1½ per cent. for all loads within working limits.

---

[1] See the earlier editions of this work. See also an interesting paper by Crocker in *Electrical World*, xiii. 311, 1889.

[2] *Phil Mag.*, January 1886.

Potential at Terminals.	Current (amperes).	Horse-power at Brake.	Revolutions per minute.	Torque (pound-feet).
68·4	44	1·1	1125	5·15
68·4	126	7·4	1120	33·4
68·4	165·5	10·36	1115	48·8
68·4	180	11·14	1110	53·0

With a lower electromotive-force the same motor regulated almost equally well, but at a lower speed. It was observed that, especially when the motor was giving out small horse-power, the speed was increased by weakening the field.

THEORY OF SELF-GOVERNING MOTORS.

The method of automatic regulation that is most perfect in theory is undoubtedly that of Professors Ayrton and Perry,[1] and is expounded in the following pages; it results in a differential compound winding.

In the section on Self-regulating Dynamos, on pp. 307 to 320, were set forth the methods of solving the problem how to arrange a dynamo so that it shall feed the circuit with electric energy under the condition of a constant pressure, when driven at a constant speed. The solution to that problem consisted in the employment of certain combinations which gave an initial magnetic field due to a shunt coil, and an increment to that field dependent on the current that might be flowing in the main circuit.

Now, it is not hard to see that this problem may be applied conversely, and that motors may be built with a combination of arrangements for their field-magnets, such that, when supplied with currents under the standard conditions of constant pressure in the mains, their speed shall be constant whatever the load. It will be evident, without any numerical calculations, that the windings must oppose one another—one must

[1] *Journal Soc. Telegr. Engineers*, vol. xii., May 1883; see also a later paper in *Phil. Mag.*, 1888.

tend to magnetize the field-magnet, the other to demagnetize. Take the case of a shunt motor supplied at a constant potential V, and running at a certain speed with a certain load. If the load is suddenly removed the motor will begin to race, its racing will increase the counter electromotive-force developed and will partly cut down the armature-current. But the decrease of current will not be quite adequate to bring back the speed, because of the internal resistance of the armature, which has prevented the whole energy of the armature current from being utilized as work. A demagnetizing series coil wound on the field-magnet will, however, effect what is wanted, for then, with any reduction of load, the corresponding reduction of current can take place, the resulting increase in the field-magnetism being sufficient to get the required larger counter electromotive-force without any increase in speed. For constant-current distribution no method of compound winding, whether differential or additive, has been found satisfactory ; special regulators must be employed.

The following synoptical table contrasts the arrangements for self-regulating generators with those of self-governed motors :—

GENERATOR.	MOTOR.
Given Constant Speed.	*To get Constant Speed.*
To get V *constant.*	Given V *constant.*
Initial magnetism { Steel magnets. Separate excitation. Shunt coils.	Initial magnetism { Steel magnets. Separate excitation. Shunt coils.
+ Series-regulating coils.	— Series-regulating coils.

In discussing the theory of the self-governed motor, we shall follow the same general lines as in discussing the theory of the self-regulating generator, namely, find an equation expressing the desired condition of constancy.

Shunt or Separately-excited Motor with Series Regulating Coil.—Using the same notation as previously, we have for the counter electromotive-force developed in the armature—

$$E = n \, Z \, N \div 10^8 = n \, M,$$

also

$$E = V - (r_a + r_m)\,C.$$

Now, M is made up of two parts, viz.:—M_1 the permanent part (which in a shunt motor is equal to $q\,S_s\,C_s$, where S_s is the number of windings in the shunt), and another part depending on the series coil which we may write $q\,S_m\,C$, where S_m is the number of windings in series; where q is written for Z multiplied by $4\,\pi$ and divided by 10^9 times the sum of the magnetic reluctances. Its value therefore depends upon the permeability, and therefore upon the degree of saturation of the iron of the magnetic circuit. Reserving this point for further consideration, we may write

$$M = M_1 - q\,S_m C.$$

If we had written + instead of –, we should find the solution coming out with the negative sign, indicating that the windings must be so arranged that the current in the series coil circulates in the negative or demagnetizing sense. We write the negative sign, however, as we already know that this must be so. We also assume at present that there are no armature reactions. Substituting the value of M in the fundamental equation, we have

$$E = n\,(M_1 - q\,S_m\,C);$$

and equating this to the other value of E in the second equation above, we find

$$n = \frac{V - (r_a + r_m)\,C}{M_1 - q\,S_m\,C}. \quad . \quad . \quad . \quad [I.]$$

Having thus obtained an expression for the speed, we must examine the various parts of the expression to see which are variable and which constant, and so deduce a relation which shall make n constant. Now, in both numerator and denominator there are two terms, the first of which is a constant, whilst the second of each contains the variable C. A little consideration will show that the fraction cannot have a constant value unless the two coefficients of the variable in the second term bear the same ratio to one another as do the two constants which stand as the first terms; or n cannot be constant unless

$$\frac{V}{M_1} = \frac{r_a + r_m}{q S_m}, \quad . \quad . \quad . \quad . \quad [II.]$$

which is the desired equation of condition.

If this condition be observed (and it will be noted that the quantity of series winding required is proportional, as in the self-regulating dynamo, to the internal resistance of the machine), then the speed will be constant and of the value

$$n = \frac{V}{M_1} = \frac{r_a + r_m}{q S_m}. \quad . \quad . \quad . \quad [III.]$$

From the first of these relations we see that the speed at which the machine is thus governed to run is the same speed as that at which, if driven as a generator on open circuit, it will yield an electromotive-force equal to that of the supply at the mains. When running as an unloaded motor, it ought of course to turn so fast as to reduce the current through its armature to a minimum, which it can do by running at this speed. It is evident that by making the permanent part of the magnetism strong enough, the critical speed—that is to say, the speed for which the motor is self-governing—may be made as low as desired. As the load on the motor is increased, the flow of current through the armature must be increased, and this increased current cannot flow unless in some way the counter electromotive-force of the armature be diminished. As the speed is to be kept up, this is accomplished by the lowering of the magnetism, which occurs in consequence of the increased current flowing through the demagnetizing coils. The quantity denoted by q, which depends on the permeability of the iron, may be taken at an average value between the two extremes which it has at maximum load and at zero load, since in a well-designed motor the resistances in the armature-circuit are very small and the efficiency as a whole high, the demagnetizing effect of the series coils, even at full-load, need only reduce the magnetization by a small percentage. Moreover, if a backward lead be given to the brushes to prevent sparking, the armature itself will act partially as a demagnetizing series coil, and so compensate for alteration in the permeability. The magnetism is a maximum when the motor is running empty. When the load is greatest, if the motor is running at, say 80 per cent. efficiency, E will be 80 per cent. of V; that is to say, M will be 80 per cent. of M_1. It is between these limits in the magnetization that the value of q must be averaged. It is evident from equation [III.] that if the motor is already provided with a given series winding, there can be found a value of V, for which the condition of self-governing can be still fulfilled. In the case of a shunt motor the above equation is capable of further simplification; for we know that $V = C_{sh} r_{sh}$, where r_{sh} is the resistance of the shunt, and $M_1 = q\, S_{sh}\, C_{sh}$. Substituting these values in [II.] above, we get

$$\frac{S_{sh}}{S_m} = \frac{r_s}{r_a \div r_m}, \quad . \quad . \quad . \quad [IV.]$$

which is Ayrton and Perry's rule for the winding of the self-governing motor. Motors wound differentially in the proportion indicated in equation [IV.] are very nearly self-governed. One very curious property of this method of winding is as follows:—Suppose the motor to be standing still and the current turned on, the ampere-turns due to the shunt will be equal to $V\, S_{sh} \div r_{sh}$, whilst those due to the series coil will be $V\, S_m \div r_a \times r_m$; and these, according to equation [IV.], will be equal, and they are of opposite sign. There should then be no magnetism excited at all. But if there is any lead at the brushes, the magnetizing tendency of the armature will come into play; and if the brushes have a considerable negative lead, the effect will be to magnetize the field magnet in the wrong sense, and then the motor starts the wrong way. The defect might be remedied by cutting out the series coil or reversing it, until the motor has got up its speed. The latter course is preferable, as the additional torque of the series motor is of great advantage in overcoming the statical resistance to motion experienced at starting.

It is obvious that the number of shunt-turns should theoretically be such that the motor, driven on open circuit at the given speed, shall generate an electromotive-force equal to V.

Predetermination of the Compound Winding.—Both the shunt and the series winding can be predetermined just as in dynamos by computing the numbers of ampere-turns (as in Chapter XVII.) of excitation required to produce V volts at the required speed, and to produce $V - C(r_a + r_m)$ volts also at the required speed; the latter excitation being that due to the difference between the ampere-turns of the shunt and series coils.

Practical Determination of the Shunt and Series Windings.—As in the case of compound windings of dynamos, so for motors, the proper windings can be found by simple experiments, a temporary coil being wound and separately excited, and a resistance equal to the future r_m being added to the armature resistance. Two experiments are required. Run the motor first with no load at the brake, using the proper pressure V, and excite the temporary coil, observing the number of ampere-turns that are needful to bring the speed down to the required n. The number of ampere-turns in this case is equal to $S_{sh} C_{sh}$, where C_{sh} is the current, which economy dictates should be used in the shunt. Secondly, run the motor with its fullest load at the brake; and again excite the field-magnet with such a number of ampere-turns that the speed is constant at n. From this and the previous experiment S_m can be calculated.

The efficiency of a differentially-wound motor cannot be expected to be quite as high as that of one which is not differentially wound, since the energy expended in the former case in magnetizing the field-magnets is greater relatively to the amount of magnetization produced.

MECHANICAL CHARACTERISTICS OF COMPOUND DIFFERENTIAL MOTORS.

It may be convenient here to consider the graphic representation of the regulations between speed and torque in motors provided with mixed windings.[1]

The curves for constant-potential supply are shown in Fig. 518. The letters M and S refer to main circuit windings and shunt windings respectively. The forms of the curves for mixed windings differ somewhat according to the proportions of the two sets of coils. The important case is that of the differential winding marked S − M, having a few series turns to correct the droop of the pure shunt-winding, and it will be noted that up to a certain limit the speed is nearly constant, but that there is a maximum value to the torque. In the case of constant-current supply, as the curves of

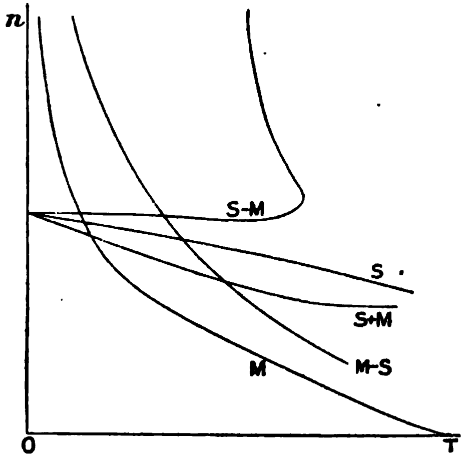


FIG. 518.
MECHANICAL CHARACTERISTICS AT CONSTANT POTENTIAL.

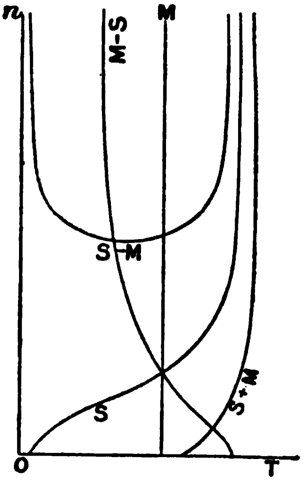


FIG. 519.
MECHANICAL CHARACTERISTICS WITH CONSTANT CURRENT.

---

[1] The author is indebted to Frölich's *Die Dynamoelektrische Maschine* for the curves of motors with mixed windings. Similar curves have been deduced by Rechniewski, see *Séances de la Société de Physique*, 1885, p. 197.

Fig. 519 show, the only winding which gives any approximation to a constant speed is the differential compound winding with a large shunt coil, and comparatively few turns of de-compounding series coil.

CONTROL OF MOTOR SPEED.

In the vast majority of cases, current is supplied to motors under the condition of *a constant voltage.* Under this condition motors with permanent magnets or with shunt excitation run at speeds which are nearly constant, but with a slight speed-drop proportional to the load. At light loads they do not race, but tend to reach a definite maximum speed. Series motors, on the other hand, vary their speed with the load, and at light loads tend to race, having no fixed maximum speed at no-load.

For many purposes, particularly for the driving of tools and for locomotion, it is desirable to have a means of controlling the speed of motors, so that a given motor supplied at a given voltage may be made to run at different speeds at will: the motor when set to any particular speed maintaining that speed with reasonable constancy even though the load upon it may vary.

To study this problem of control we may refer to the fundamental expressions for torque and speed given by equations [5] and [6] on p. 812. The equation for speed is:—

$$n \text{ (in } \textit{revs. per sec.}) = \frac{V}{M} - \frac{8{\cdot}52\, r\, T}{M^2} \quad . \quad . \quad [6]$$

where V is the voltage of supply; r the resistance through the motor from terminal to terminal including the armature rheostat, if any; T the torque on the armature in pound-feet; and M the effort-factor (see p. 811). The expression consists of two terms, the first being the speed at no-load, the second being the speed-drop proportional to the load. To appreciate further the significance of this expression, let us assume that the motor is to be set to turn against the reaction of some definite counter-torque such as that of raising a weight upon a pulley. It is obvious that the resisting torque in this case is independent of the speed of running. We might, instead, consider the resisting torque of a boring tool, or of a line of shafting driving machinery ; but in these cases the assumption that the torque would not vary with the speed would be far from the truth. Assuming, then, that T is constant, we see that increasing V will increase the speed, and that increasing M will lower the speed (since the first term is more important than the second term), while any increase of r will also lower the speed. *We have, then, three ways of varying the speed*, namely by altering any one of the variables V, M, or r.

The quantity M is not a constant in a motor supplied at constant voltage, even though its magnetic flux may be constant. For if V is constant, the motor's counter electromotive-force E will be less by an amount proportional to its internal resistance and to the current through its armature, which current is approximately proportional to the load on the motor. In fact, if we consider equation [6] we can solve it as a quadratic of the quantity M ; the solution being

$$M = \frac{1}{2}\frac{V}{n}\left(1 \pm \sqrt{1 - \frac{34{\cdot}08\, n\, r\, T}{V^2}}\right). \quad . \quad [7]$$

If r were zero this would obviously reduce to the value $V \div n$.

I. *Control by Change of Voltage.*—Assuming the magnetism to be constant and independent, if the voltage applied to the armature at the brushes is altered, the no-load speed ($= V / M$), changes in precise proportion, but the speed-drop from no-load to full-load remains unchanged. Thus if such a motor running at 1000 revs. per min. on 500 volt mains, with a drop to 950 revs. per min. at full-load, were removed to a place where the supply voltage was 400 volts, it would run at 800 revs. per min., dropping to 750 at full-load. It has been proposed for example to give a motor four different speeds, when worked on a 500-volt system, by introducing a 5-wire system of distribution with 125 volts between each set of mains (as in Fig. 520), thus enabling the motor to be worked at will on 125, 250, 375, or 500 volts. The required subdivision of the voltage could be maintained by a "balancer" (p. 776), or by a set of accumulators ranged between the mains.

Another way of altering the voltage on such motors is to introduce into the conducting circuit of the armature the counter electromotive-force of one or more accumulator cells or an armature that is acting as a generator. There are also special modes of varying the voltage by means of motor-generator combinations, including the particular Ward-Leonard method of regulation mentioned below.

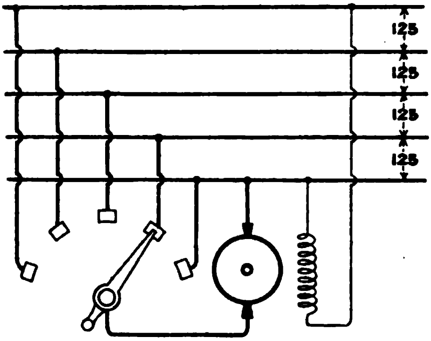


FIG. 520.—VARIABLE SPEED MOTOR.

II. *Control by altering the Magnetic Flux.*—Since M is proportional to the flux that enters the armature, it can be altered by altering the magnetic flux. There are four ways of effecting this :—

(*a*) In the case of series-motors by varying a resistance that is applied as a shunt to the magnet coils to divert any required fraction of current from them.

(*b*) In the case of shunt-motors, by varying a resistance, or *field rheostat*, that is put in series with the exciting coils.

(*c*) By altering the grouping of various sections of the magnet-winding by a suitable switch or controller. Fig. 521 is a diagram of this arrangement.

(*d*) By varying the reluctance of the magnetic circuit, as for example by arranging the pole-cores so that they can be withdrawn to a greater distance from the armature; or by magnetically shunting part of the magnetic flux. Such devices are only available for small motors.

In any case a reduction of the magnetic flux causes an increase in the current taken by the motor from the mains, and an increase in its speed because of the lowering of the counter electromotive-force.

III. *Control by introducing Resistance into the Armature Circuit.*—This is a simple, but wasteful mode of regulating. It is akin to the first method, because if a resistance *r* is interposed in a circuit carrying C amperes, a voltage drop of C *r* volts is therefore produced, virtually reducing the voltage of supply, not by a fixed amount but by an amount proportional to the load. At light loads introducing a given resistance has a less effect in reducing speed than the same resistance would have if the motor were on a heavy load. For an account of motor-starting rheostats, see Chapter XXVI.

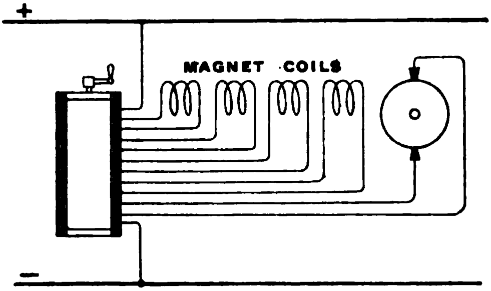


FIG. 521.—MOTOR WITH CONTROLLER TO VARY NUMBER OF EXCITING COILS.

IV. *Control by Grouping two or more Motors in Series and Parallel.*—A more effectual way of changing the speed of motors consists in taking two (and the method is applicable to four) motors of similar construction and arranging them so that they are mechanically coupled ; while they are connected electrically to the circuit so that they can be put either in series or in parallel with one another. When thus in series each armature only gets half the voltage from the mains, and hence they tend to run at only half the speed that either alone would run at, or that the two will run at when in parallel. This arrangement of series-parallel control was suggested by Hopkinson for tramcar propulsion. It is further considered below.

V. *Control by Two-Commutator Motors.*—A useful variant on this use of two motors consists in the use of one motor having its armature wound with two separate windings, each with its own commutator, with arrangements to use in series or parallel. This device is excellent for automobile vehicles.

ACCELERATION OF MOTORS.

In motors for mill and factory use the time taken by the motor to run up to its proper speed is unimportant, and is usually a very short time: in such motors the question of giving adequate power at the required speed without over-heating or sparking is the important one. But in motors that are to be used for locomotive purposes in tramcars, or automobiles, or on railways, the question of time taken to get up speed is very important. In other words, the *acceleration* of the motor is more important than its horse-power. To start a tramcar, automobile, or train, requires in each case a certain minimum effort on the motor shaft. To maintain in a uniform motion the tramcar, automobile, or train that has already been started requires also a certain continuous effort on the part of the motor. If the effort of the motor exceeds that so required for uniform motion, *the excess of the torque goes to accelerate* the movement. The acceleration will be proportional to this excess of torque. Now we have seen, in equation [4], that the torque is proportional to the product of the quantity M of the motor multiplied by the current flowing through it; or

$$T \text{ (in pound-feet)} = 0{\cdot}1175\ MC_a.$$

The product MC_a therefore becomes of definite importance in accelerating the speed. It may therefore be called the *effort-product.* It is equivalent to 8·52 times the force in pounds' weight, which would be exerted by the motor at the rim of a wheel the radius of which was one foot. Now it is clear that either for the purpose of starting under a heavy dead-load as in the case of lifts, or for producing a rapid acceleration, a motor must have a large *effort-product*, quite apart from the question of its nominal or actual horse-power. Consider a lift with a dead-weight of 1000 lb. to be raised. A motor is suitably geared to the lift. Whatever its horse-power it must, in order to start at all, be able to exert a definite effort. Assume that it has a sufficient effort-product: then if it actually works at one horse-power (net) it will raise the 1000 lb. at the speed of 33 feet per minute; while if it works at two horse-power it will raise the 1000 lb. at the speed of 66 feet per minute. A motor with a large *effort-product* will more quickly get up to the speed corresponding to the available horse-power. Now, as this product is the product of the effort-factor M and C_a, and as a large current implies costly working and internal heating, it is obvious that the motor that is to accelerate well, and not take too much current, must have a large M. In other words, it must be a slow-speed machine relatively to the voltage at which it is to be worked, since M is the induced electromotive-force per revolution.

Magnetic Braking.—Any motor that is revolving can be effectively braked by simply short-circuiting it through an appropriate resistance. This is used in many tramway motors. The armature generates currents which for the moment heat the coils but which rapidly bring it to rest. To brake a series motor, the motor must be disconnected from the mains, and the connexion of its exciting coils to the armature reversed.

MOTOR EQUIPMENTS FOR PARTICULAR PURPOSES.

With the application of motors to industrial purposes many developments have been called for. In factory equipment, if the tools are belt-driven from short lines of motor-driven shafting, the motors must be of constant speed, and all speed-changing on any tool must be effected mechanically. But if each tool is driven by an individual motor, then, generally, each motor will be of the particular speed needed for each tool, and many of them must therefore be variable-speed motors. A variable-speed motor costs more than a constant-speed motor of equal power, since, apart from the cost of the switch-gear or controller to change the speed, the variable-speed motor must, as to its cost, be rated on its lowest speed. For cranes, hoists, and tramway driving, where uniformity of speed is not the prime consideration, the usual equipment is a series-motor with rheostatic control, or sometimes with two series-motors with a series-parallel control combined with rheostatic speed control. For pumps and air-compressors which need a constant torque, and for fans and blowers needing a torque that increases with the speed, the proper equipment is a compound-wound (not differential) motor with a rheostat in the shunt-winding; the use of the series-coil being here to prevent the heavy draught of current through the armature that would occur if a mere constant-speed shunt motor were used. For textile factories motors are needed of absolute uniformity of speed; and for these three-phase alternating motors are much to be preferred. A less satisfactory solution is the compound (differential) motor. For machine tools variable-speed motors are needed. In the case of milling cutters, planers, and slotters, the range of speed-variation is seldom greater than from 1 to 2; whereas lathes and boring-mills need a range of speeds as great as the range of diameters of the jobs on which they work. Thus, taking as an example a kind of lathe work for which the proper cutting speed of the tool is 50 feet per minute, if a wheel 5 feet in diameter is to be tooled it must revolve at 3·2 revolutions per minute, while if a 7-inch shaft is to be turned up it must revolve at 26·4 revolutions per minute. Here is a speed-variation of 1 to 8. Now, taking the case of a shunt motor on an ordinary constant voltage supply, what variations of speed are possible? Changes in two directions are possible—reduction of speed by armature rheostatic control, and increase of speed by field excitation control. The shunt exciting coils are joined across the mains to receive full voltage: the armature rheostat lowers the speed by putting in resistance. Suppose it has reduced the speed by 50 per cent. It has also reduced the power and efficiency of the motor in precisely the same proportion. Rheostatic control is always wasteful; for even a reduction of speed to one-half it requires large and heavy rheostat coils. If the rheostat is arranged, as it should be, with the resistance subdivided between a number of points of contact to vary the speed by successive steps, yet the transition from one speed to another always occurs with some abruptness. Also at the lower speeds, the speed is not constant but is found to change with the load because the proportion of the voltage actually received by the armature varies with the load. Rheostatic control is, therefore, at the best a make-shift method of control. On the other hand, the field-control by putting resistance into the exciting circuit weakens the field and so raises the speed. There is nothing wasteful about this method of control. As the magnetism of solid field-magnets requires a measurable time to change, it is found that on this method the transition from one speed to another occurs quite smoothly. But there is the serious disadvantage that the range of speed increase is limited to some 30 or 40 per cent. at the most, because as the field is weakened the spark troubles begin.

This difficulty of speed-change in the motor itself has led to the suggestions noted above to operate motors on a multi-voltage system, or to employ series-parallel combinations of two (or more) motors. In the case of multi-voltage systems using a 3-wire, or a 4-wire, or a 5-wire distribution, there is the increased cost and complication of the wiring, and the expense also of the multi-voltage balancer; and the motor must be big, as it has to do its full power at the minimum speed. Nevertheless, this method affords a means of working a shunt motor at two, three, four, or more definite speeds, corresponding to the voltages. In the case of a series-parallel control with two combined motors, or with one two-commutator motor, the speed of the machine in the series position is half of the speed in the parallel position, assuming the field-magnets to be equally excited in the two cases. Neither multi-voltage alone, nor series-parallel alone, affords a speed-range so great as 1 to 8, and they both afford merely a means of changing by wide steps to definite speeds. Neither of them alone, therefore, meets the needs of a variable-speed tool requiring both wide range and all possible intermediate speeds at will. For such intermediate speeds a solution can be found by combining with either multi-voltage or series-parallel, the rheostatic reduction and the field-control increase methods just mentioned. In Chapter XXVI. are described the controllers by which such wide variations of speed are attained.

Printing machines require to run at a high speed when in ordinary work, but, when making up or threading, to run at, say only 10 to 15 revolutions per minute. For them, therefore, some kind of variable-speed motor is needed, with smooth transition from one speed to another. Multi-voltage motors have been used for this purpose, also double commutator motors with an extra series coil thrown into circuit only at starting, and series-parallel control. But far preferable have proved in practice the compensation or reducer methods described below.

Important discussions upon the adaptation of motors for factory and mill work, of their speed-regulation, gearing, grouping, starting and control, will be found in the *Journal of the Institution of Electrical Engineers*, vol. xxxii., August 1902, in papers by A. D. Williamson, p. 925; A. B. Chatwood, p. 964; and A. H. Bate, p. 1088; also in the *Transactions of the American Institute of Electrical Engineers*, xix. pp. 1537 to 1606, December 1902, in papers by C. F. Scott, R. Lozier and others.

COMPENSATION METHODS OF MOTOR CONTROL.

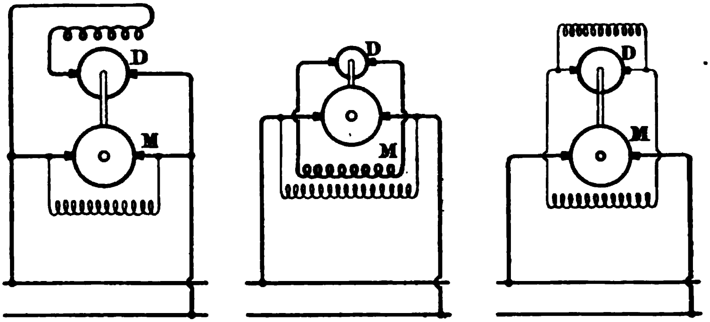
We have seen that there is a direct analogy between the compounding of a dynamo to give constant voltage at constant speed, and the compounding of a motor to run at constant speed on mains of constant voltage. We have also seen that in the case of a generator it is possible to substitute for compounding the process of boosting, by auxiliary use of a motor-driven auxiliary generator.

Analogous considerations apply to the problem of driving motors from constant-potential mains, for by combining with the motor which is to be driven (or with an auxiliary motor) an armature which performs the part of generator, one may apply the electromotive force so generated to raise or lower the voltage that is imparted to the motor, so changing its speed. The compensation method was invented by Ayrton and Perry[1] who applied it for the purpose of keeping motor speed constant under varying loads. One of their methods is shown in Fig. 522*a*. The motor, M, to be driven is coupled mechanically to a smaller dynamo, D, in this case a series machine, arranged to add its current to that coming in from the mains. Fig. 522*b* depicts a combination due to Mordey and Watson (1885). The armature in this case has two windings with separate commutators, or two armatures, both within the same field-magnet. The main armature is the motor, the other, a small armature marked D in Fig. 522*b*, acts as a generator and simply supplies additional current to the field-magnet. Assume the machine to be running at a certain speed on a certain load. Then when the load is lessened, any increase of speed tends, at once, to strengthen up the field and so bring down the speed to its normal rate. In another plan, Fig 522*c*, patented by Lamme, the auxiliary generating armature supplies the current to its own shunt-field, and to the field of the motor also. Fig. 522*d* is a modification of the original Ayrton and Perry plan to put the armature of the auxiliary dynamo in series with that of the motor it is to control. Changes of speed can be effected by rheostats in the shunt of either armature. Insertion of resistance in either shunt circuit raises the speed.

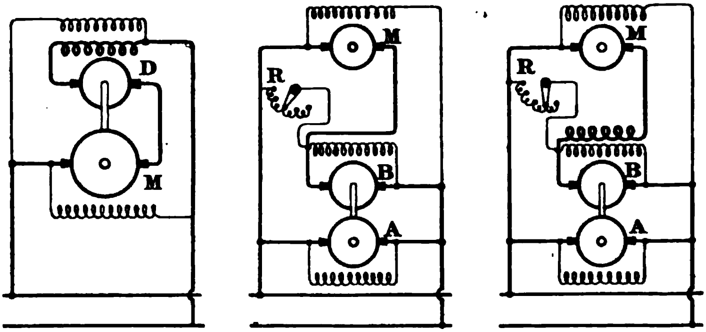
The combination depicted in Fig. 522*c* represents an arrangement in which the dynamo B inserted in the main circuit of the motor M is not driven by the latter, but by an auxiliary motor A, which takes its current direct from

---

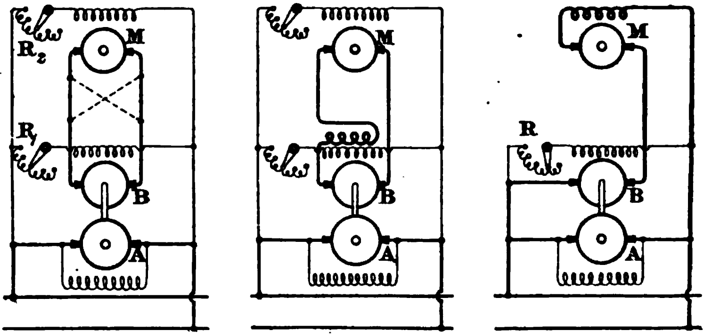
[1] *Journal Soc. Teleg. Engineers*, xii., May 1883.



(*a*) AYRTON & PERRY (*b*) MORDEY & WATSON (*c*) LAMME



(*d*) S. P. THOMPSON (*e*) SHUNT BOOSTER AS REDUCER (*f*) DIFFERENTIAL BOOSTER AS REDUCER



(*g*) WARD LEONARD (*h*) DERI (*i*) ESSBERGER

FIG. 522.—DIAGRAMS OF COMPENSATION AND REDUCER METHODS.

the mains and runs at a nearly constant speed. The field magnet of the dynamo is excited by a shunt across the mains, with a controlling rheostat R inserted. At starting this rheostat is put at zero resistance, so that the dynamo yields its highest electromotive-force counter to that of the mains, when the motor M is switched in it therefore receives a greatly reduced voltage. The rheostat is then moved step by step reducing the electromotive-force of the dynamo and increasing the voltage given to the motor M, the speed of which rises accordingly. Fig. 522*f* shows a variety in which a differential booster is similarly used as a reducer. Fig. 522*g* depicts the special device of Ward Leonard,[1] which is practically the reverse of the preceding arrangement. The shunt booster is here employed, not to reduce the voltage of the mains, but to create a variable voltage that is directly applied to the motor M. Two rheostats, R_1 in the exciting circuit of the booster generator B, and R_2 in the exciting circuit of the motor M, control the speed. At starting, R_1 is set with all resistance in, so that the voltage generated by B is as low as possible, while R_2 is set at zero so that the motor's field is as strong as possible. The highest speed is obtained when the positions are reversed. Ward Leonard has devised many varieties of this idea to adapt it to a 3-wire system and for reversing the motor as required in elevators. Fig. 522*h* is a modification due to Déri[2] employing a differential booster. Fig. 522*i* is a recent combination by Essberger,[3] in which a shunt booster is employed as reducer for a series motor.

In the systems known as the Bullock Teaser and Spence's Reducer, a motor-generator is combined with the main motor in the manner diagrammatically indicated in Fig. 523, and which differs from any of the preceding in that the changes of speed are brought about by rheostats placed in the armature circuits of the two motors, and not in their exciting circuits.

---

[1] British Patent, No. 14503, of 1891; U.S. Patents, Nos. 463802 and 468100. See also *Proc. Amer. Instit. Elect. Engineers*, Nov. 18, 1896, also *American Electrician*, Nov. 1902.

[2] British Patent, No. 11523 of 1902.

[3] British Patent, No. 22031 of 1901.

One disadvantage of these booster and reducer methods is the cost of the auxiliary apparatus. For example to drive with variable speed a coal hoist, the motor being a 6-pole machine rated at 75 kilowatts at a normal speed of 200 *r.p.m.*, and working at 250 volts, there was required an auxiliary motor, also 6-pole, rated at 112 kilowatts at a normal speed of 450 *r.p.m.*, working on the mains at 550 volts, and driving a 6-pole generator rated at 85 kilowatts at 450 *r.p.m.*, generating 250 volts. Each of the auxiliary machines composing the booster was therefore a machine of the same class as the hoist motor and of larger size. The extreme flexibility of the system and the smoothness and economical nature of the control, are, however, such as to justify the increased outlay.

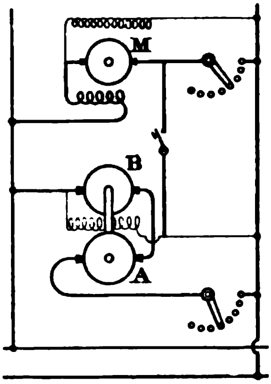


FIG. 523.
REDUCER WITH
RHEOSTATIC CONTROL.

DESIGN OF CONTINUOUS-CURRENT MOTORS.

As a motor is simply a dynamo reversed in its functions, the same general principles govern its design as those which govern the design of generators. Indeed, large motors may be and often are identical in their design with generators. Where, however, one large generator is required to furnish current, there are usually required a number of smaller motors. In the design of small machines there arise innumerable little details and differences special to individual manufacturers. It must suffice here to deal only with generalities, and foremost amongst them the point that for securing satisfactory commutation, the field-magnet must be relatively strong. Carbon brushes being now almost universal for motors, there is less trouble on this score than used to be the case. Motor design often resolves itself into some special problem.

for example, how to construct the armature to give the required power while not exceeding some prescribed length, as is the condition in railway motors, or how to construct the motor so that while wholly enclosed it shall not overheat. Again, the design of fan-motors is mainly a question of designing to suit special processes of manufacture in quantity requiring the smallest amount of machining or hand-labour.

Useful Formulæ in Design.—Although, as remarked above, a motor *might* be designed simply as a dynamo of the equivalent number of kilowatts, it is possible to proceed on an independent plan. *The size of the armature depends primarily only on the torque which the motor is normally required to exert,* and does not directly depend upon its speed. Hence given the torque, it is possible to deduce the appropriate size of armature. In the argument that follows, the symbols have the same meanings as in Chapter XVIII. on Dynamo Design, viz. C_a = whole current in armature; C_1 = current in one conductor; c = number of armature circuits in parallel; p = number of poles; q_1 = ampere-conductors per inch of periphery; B_g = mean flux-density at the pole-face; ψ = ratio of equivalent pole-arc to pole-pitch; and T = the normal full-load torque, in pound-feet.

Then, starting with the fundamental motor formula, we have, from p. 812,

$$T = 0{\cdot}1175\, M\, C_a;$$

also

$$M = \frac{p}{c}\, Z\, N \div 10^8;$$

further

$$C_1 = C_a \div c;$$

$$q_1 = C_1\, Z \div \pi\, d;$$

and

$$N = B_g \times \psi \times l \times \pi\, d \div p.$$

Inserting these successively into the first equation, we get:

$$T = 0{\cdot}1175 \times B_g \cdot \psi \cdot q_1 \cdot \pi^2 \cdot d^2 \cdot l \div 10^8;$$

whence

$$d^2 l = 86{\cdot}3 \times 10^6 \frac{T}{B_g \cdot \psi \cdot q_1}. \qquad \text{[I.]}$$

This formula may be compared with the corresponding formula for dynamo-design on p. 542. To apply this formula we must know from experience what are the appropriate values for B_g, ψ, and q_1 respectively. In tramway motors we may take as typical values $B_g = 66{,}000$; $\psi = 0{\cdot}7$; $q_1 = 500$ to 520. In small motors of 1 to 5 H.P., the values of B_g and q_1 are somewhat lower, and in those of less than 1 H.P are seldom half as great. If we assume the above values for tramway motors we may at once deduce

$$d^2 l = 3{\cdot}64\,T. \qquad \text{[II.]}$$

Example.—A narrow-gauge tramway motor is required to exert a normal torque of 630 pound-feet; required the diameter of the core, the length between core-heads being limited to 9 inches. By the preceding formula $d^2 l = 630 \times 3{\cdot}64 = 2300$. Hence $d^2 = 2300 \div 9 = 255$. So that $d = 16$ inches.

Another useful formula, analogous to [IV.] on p. 542, is:

$$d^2 l = \xi \frac{\text{H.P.}}{r.p.m.}; \qquad \text{[III.]}$$

where

$$\xi = 45{\cdot}36 \times 10^{10} \frac{1}{B_g \cdot q_1 \cdot \psi \cdot \eta}; \qquad \text{[IV.]}$$

the symbol η being the efficiency including the efficiency of the gearing.

Example.—To find the size of the armature core of a slow-speed motor of 2 H.P., at 900 revs. per min. Assume $B_g = 48{,}000$; $q_1 = 185$; $\psi = 0{\cdot}75$; $\eta = 0{\cdot}85$. Then $\xi = 80{,}000$; and $d^2 l = 177$. Hence following trial-values:—

$$\left.\begin{array}{l} d = 6{\cdot}5;\ l = 4{\cdot}5 \\ d = 7{\cdot}0;\ l = 3{\cdot}55 \\ d = 7{\cdot}5;\ l = 3{\cdot}15 \end{array}\right\}.$$

Of these, for a 4-pole semi-enclosed type, the best proportions are given if $d = 7$ inches.

The number of poles will be settled in small motors by considerations as to construction, and in large ones by the desirable number of armature circuits. From the number of poles and the trial values for d and l, trial values are got for the size of pole-face and of the magnetic flux. Multiplying the perimeter πd by the specific load q_1, gives the total ampere-conductors around the armature, and this, divided by the current in one conductor, gives Z. Then from Z, N, and the prescribed voltage, one finds the normal full-load speed. This is, of course, known if the normal full-load torque and horse-power are prescribed; and in that case Z may be calculated from speed, flux, and voltage. The trial-value of Z so found must then be adjusted in the usual way to suit the winding and for proper grouping in the slots. To meet this adjustment it may be needful to adjust d and N or both. In adjusting Z, regard must be had to the number of segments K of the commutator; for in motors it is common to have several loops of winding per segment. The number of loops per segment is fixed by the voltage of the machine, and the permissible number of volts per segment. In 500-volt motors this sometimes runs as high as 20 or even 22 volts. The example given later will make this point clear.

Another possible procedure in designing a motor for a vehicle is to begin by ascertaining the *effort-factor* M from the prescribed draw-bar pull, size of driving-wheel, gear-ratio, and the normal full-load current. In this case formula [VIII.], p. 814, is applicable and may be written

$$M = 4{\cdot}2\, P\, D_w \div g\, C_a \,; \qquad . \qquad . \quad [\mathrm{V.}]$$

where P is the draw-bar pull in *pounds'* weight; D_w the diameter *in feet* of the driving-wheel; and g the gear-ratio.

Example.—In the "G.E. 52" motor taking 51 amperes, and with a gear-ratio of 4·78 (i.e. gear-wheel 67 teeth, pinion 14 teeth), with driving-wheels 33 inches (= 2·75 feet) in diameter, to give a draw-bar pull of 830 *pounds'* weight, the value of M must be :—42 × 830 × 2·75 ÷ (4·78 × 51) = 39·3.

An example of tramway motor design carried out in detail is given in Hanchett's *Modern Electric Railway Motors* (New York, 1900).

For factory and mill motors design follows more nearly that of dynamos. The example of a 3 kilowatt dynamo given on p. 644, would serve equally well for a 4 H.P. open motor. To adapt its form as a semi-enclosed motor of 4 H.P., or an enclosed motor of 3 to 3½ H.P., the field-magnet should be re-designed with a cylindrical yoke having end-flanges to which the end frames can be bolted. There would be 4 magnet cores, each about 3 inches long, making the external diameter of the yoke about 17 inches.

The current designs of small motors of special type for fans, are described in the *American Electrician*, xii. 167, April 1900; xiii. 158, April 1901; and xiv. 116, March 1902.

EXAMPLES OF CONTINUOUS-CURRENT MOTORS.

Seeing that any good dynamo, large or small, will serve as a motor if supplied at the appropriate voltage, it might have been supposed that any separate description of motors was superfluous. But the requirements in the various industries of motors, and particularly of small motors adapted to particular needs, have led to the evolution of special types.

The ordinary motors of to-day may be classified as *open*, *semi-enclosed*, and *enclosed* motors, the latter being employed in those factories where for reasons of avoiding fire-risk, the moving parts must be absolutely protected from access. Enclosed motors were first introduced in mining, and for tram-car propulsion, but their use has widely spread in spite of the circumstance that they are heavier, and for an equal rise of temperature must be rated as of some 15 to 20 per cent. lower in power than open motors of equal size.

The Crocker-Wheeler Co., of Ampere, N.J., has long made a speciality of small motors. Fig. 524 gives a view of the bi-polar open motor of this firm. Each magnet limb is stamped in one piece out of wrought-iron or mild steel, and set firmly in a cast-iron bed. The armature is built up of toothed core-plates (Fig. 287, p. 426) and ring-wound; the finished armature being represented in Fig. 525. A starting-gear is usually provided with these motors consisting of a switch, with resistances, so arranged that the field-magnet is first excited, the armature then thrown into circuit with a resistance which, when the motor acquires speed, is cut out by a further movement of the starting switch. For use in arc-lights circuits[1] a centrifugal governor is added to the shaft.

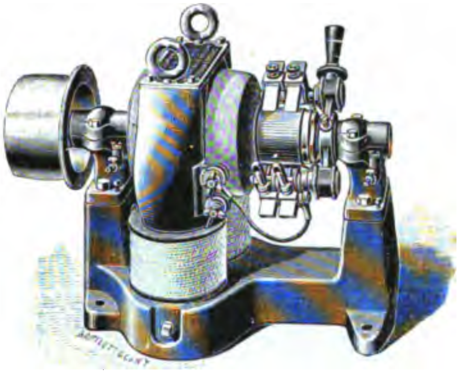


FIG. 524.—CROCKER-WHEELER MOTOR.

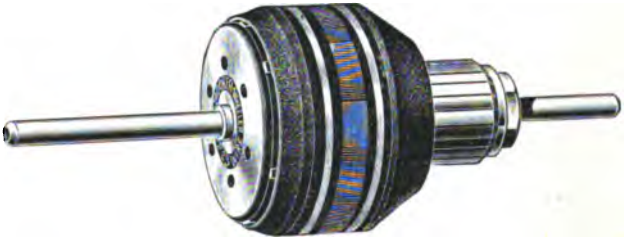


FIG. 525.—ARMATURE OF CROCKER-WHEELER MOTOR.

For sizes up to 10 H.P. the bi-polar type is used, but for large sizes 4-pole designs of the type of Fig. 417 are preferred.

---

[1] For some accounts of motors for constant-current circuits, see *Electrical World*, xv. 269, 1890; xvii. 120 and 130, 1891; also *Electrician*, xxv. 16, 45 and 131, 1890.

For further accounts of the Crocker-Wheeler motors, and their application to driving workshop tools, the reader is referred to the technical journals.[1]

Another popular form of motor is that designed by Mr. R. Lundell. The form of field-magnet of this type is depicted in Fig. 68, p. 125.

Standard series of factory motors are now put on the market by many manufacturers, such as Messrs. Greenwood and Battley, Messrs. Tangye, Messrs. Laurence Scott & Co., the British Thomson-Houston Co., the General Electric Co., and others.

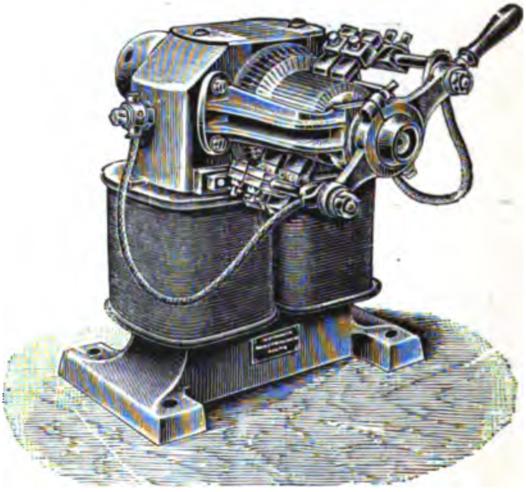
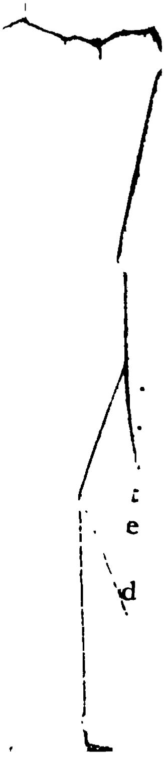


FIG. 526.—A.E.G. OPEN BI-POLAR MOTOR.

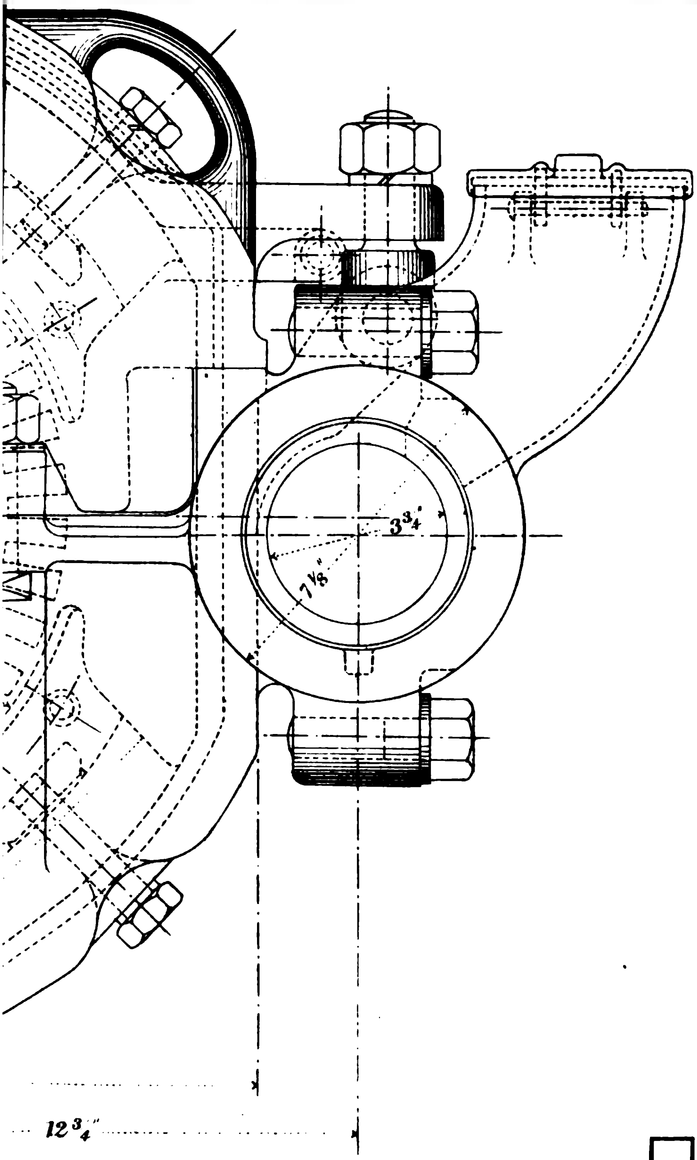
In Germany the Allgemeine Elektricitäts Gesellschaft has made a speciality of small motors, both for continuous-current and alternating. Their typical form up to 12 H.P. is shown in Fig. 526. For larger outputs 4-pole and 6-pole machines are used. This company has long systematized its manufactures. The following table includes the usual sizes:

---

[1] See *Engineering*, xliv. 83, 1887; also *Electrical World*, ix. 4, 9 and 203; xiii. 309, 1889; xv. 114, 269 and 370, 1890; xvii. 130, 191. Also see Professor Crocker's book, entitled *Practical Management of Dynamos and Motors*, and a series of papers by Professor Crocker in *Elect. Engineer* (N.Y.), 1891 and 1892.


e
d

raulique, Charleroi.



H.P.	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	1·5	2·5	4	6	10	20	30	40	60	90
Revs. per minute.	1600	1100	2100	1900	1650	1480	1270	1100	1020	925	850	720	650	600	450
Total wt., kilos.	30·5	50·5	55	75	120	220	355	385	520	825	1820	2370	2980	4100	4760
Amperes at 105 volts.	1·3	2·5	2·9	5·0	9·5	14·4	22·2	34·3	50·8	82·9	170	255	355	510	700

Since the introduction of the compact three-phase induction motors, the design of small continuous-current motors has greatly changed. They are now almost always made with 4 poles projecting inwardly from a surrounding cylindrical yoke; and the bearings, instead of standing upon separate pedestals, are bracketed out on end-plates screwed to the yoke, thus securing alignment by the simplest means. In the case of totally enclosed motors the output is limited by the amount of external surface, and the internal temperature-rise. Messrs. Mather and Platt provide the yokes of their motors with external ribs to furnish a large cooling surface.

For motors of moderate size at low voltages up to 150 volts one finds both lap-windings and wave-windings; while for 400 to 500 volts it is preferred to employ former-wound coils with a series grouping. For example, a well-known firm designs its semi-enclosed 10 H.P. motor at 440 volts with 25 slots only, containing 25 former-wound coils, each of 20 turns making 40 wires per slot, each wire being 80 mils in diameter covered to 96 mils. The slot insulation in this case is of micanite and tough paper preparations. But, using the same magnet-frame, and an armature of the same size, to run at the same speed (850 revolutions per minute), but at 110 volts, the same makers use core-disks with 65 slots, there being 65 former-wound coils, each of 2 turns; each slot having 4 wires 172 mils in diameter covered to 184 mils. The slot insulation in this case is simply varnished hard cardboard. This motor is rated at 13 H.P. as the lower voltage permits of more of the slot-space being occupied by copper.

Plate XXVIII. depicts a 30 H.P. tramway motor supplied to the Bradford Corporation by Messrs. Witting, Eborall & Co. It is rated at 30 H.P., that being the load it can stand for one hour without undue heating (i.e. a rise not exceeding 75 deg. Centig.) with cover closed, and is specified to give a draw-bar pull of 1000 lb. when running at 10 miles per hour on 30-inch wheels. The gear-ratio is 4·6, the pinion having 13 teeth and the gear-wheel 60. The normal motor-speed is, therefore, 560 revolutions per minute. The armature is a drum with 37 former-wound coils of 12 turns each, lying in 37 slots of dimensions 0·5 wide by 1·313 inch deep. The diameter of the core is 13·4375 inches, and its gross length 5·905 inches. The slots are insulated with micanite, each armature "coil" being separately insulated and baked before placing in the slots; they are held in place by wooden strips and binding-wires. The field frame is cast in two bowl-shaped pieces hinged together so as to be dust-proof and water-proof. The field-magnet is four-polar with pole-cores built of laminations bolted to faced seatings from the outside. The stampings forming these poles are of the softest sheet-steel, uninsulated but provided with a ventilating duct in each pole. All the poles are wound. The coils are wound on a former, then wrapped with micanite cloth, then taped, finally impregnated with an oil- and water-proof varnish and baked. They are held firmly against their seatings by the projecting pole-tips. The weight of the motor without gear-wheel or gear-case is 1480 lb. Fig. 515 gives the test-curves of this machine, and shows that the efficiency is high over a considerable range of load. The temperature rise at the end of a working day is not more than 55 deg. Centig. for the armature and 60 for the field system. Owing to the high saturation of the teeth, the motor runs sparklessly at all loads.

The late Professor S. H. Short published in the *Electrical Review*, xlviii. 545, 589, March 29, and April 5, 1901, an account of the construction of a 25 H.P. tramway motor of Messrs. Dick, Kerr & Co. The general design of this machine is very similar to that last described. The laminated field-poles have two ducts for the circulation of air. The former-wound coils after being taped and water-proofed, are forced over a thin bronze sleeve which is slipped over the pole-cores before the latter are bolted to their seatings. The armature-core is constructed of disks with 41 slots and provided also with 5 ventilating apertures; 2 ventilating-ducts are also left in the core-body. The armature-coils are former-wound, of triple cotton-covered round wire. Each separate coil is stoved, dipped into insulating-varnish, and dried, this process being repeated several times. Three such coils are laid together in a trough made of mica, press-board, and linen for slot-insulation, and are then taped together with two layers of thin webbing. The triple coil is again dipped in varnish and baked. The 41 such compound coils thus contain 123 separate coils, which are joined up in the manner shown in Fig. 251, p. 402, and are united to a commutator with 123 segments.

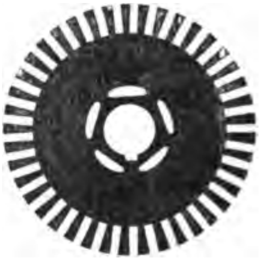


FIG. 527.—CORE-DISK OF TRAMWAY MOTOR.

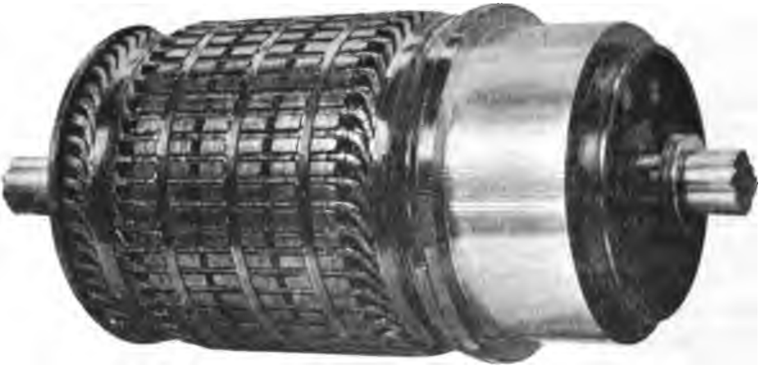


FIG. 528.—COMPLETED MOTOR ARMATURE (S. H. Short).

Each coil spans over 10 armature-teeth. Fig. 528 shows a completed motor armature of the type described.

Parshall and Hobart, in their book on *Electric Generators*, describe in detail a 27 H.P. tramway motor of the General

Electric Co. running at 640 revolutions per minute and taking 51 amperes at 500 volts. It gives a draw-bar pull of 770 lb. weight, when running at 13·1 miles per hour on wheels 33 inches in diameter, with a gear-ratio of 4·78. It is a 4-pole machine with a two-circuit former-wound armature having 29 slots, with 87 former-wound compound coils, therefore, three to each slot, each such coil consisting of 4 turns. Hence, there are 24 wires in each slot, making the total number of "conductors" 696. The wire has to carry 25½ amperes and is 102 mils in diameter. The slots are 1·29 × 0·4687 inch. The gap is 0·125 above and 0·156 below the armature. The core-body is 11 inches in diameter by 9 inches long, with 2 air-ducts. The commutator, with 87 segments, is 8 inches in diameter and 4 inches long, with mica insulation 108 mils thick. There are 2 carbon brush-sets, each of 2 brushes with face 1¼ × ½ inch.

The magnet-cores, built of stampings, are 4·375 inches wide assembled to a thickness of 9 inches and 3·875 inches long. The 4 field-magnet coils, which are in series, have 156½ turns each of wire 182 mils diameter. The mean length of 1 turn is 36 inches. The total resistance (hot) of all 4 coils is 0·76 ohm. The armature resistance (hot) is 0·36 ohm. The various drops at full-load are :—armature 18·3 volts, magnet-coils 38·6 volts, brush contacts 2·4 volts, total 59·3 volts. The current densities are :—armature 3130, magnet-coils 1920, brushes 40·8 amperes per square inch. The full-load flux is 2·96 megalines in the armature, and 3·75 in the pole-core, the dispersion coefficient being 1·25. The magnetic densities at full-load are :—armature 177,000 (apparent), teeth 144,000 (apparent), gap 66,000, pole-core and yoke 96,000. Of the exciting ampere-turns 37 per cent. are spent on the gap, 34 per cent. on the armature-core, 21 on the teeth, 8 on the pole-core and yoke. The specific load is 513 amperes per inch of periphery. The average voltage per segment is 21. The reactive ampere-turns per pole are 2200. The losses are distributed as follows :—armature iron 1120 watts, armature copper 925, magnet coils 2000, commutator and brushes 218, friction of gearing 1200, total 5463 watts. The output at rated capacity is 20,200 watts. Hence, input is 25,663 watts, and efficiency 79 per cent. The weight, without axle, gear and gear-case, is 1460 lb.

It will be noted how differently the losses are apportioned between the parts as compared with the apportionment usual

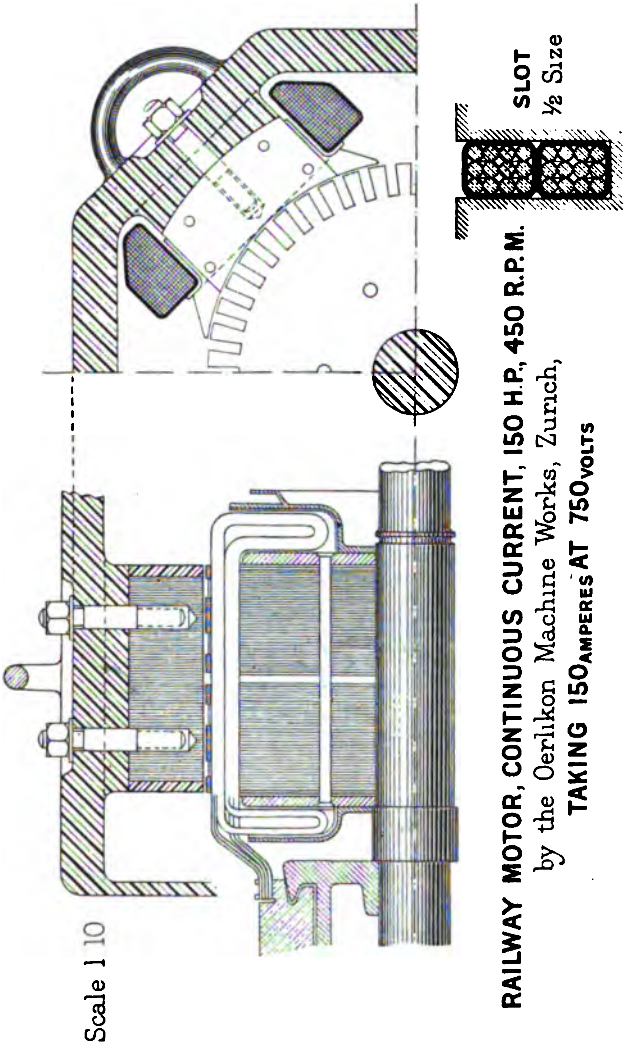

RAILWAY MOTOR, CONTINUOUS CURRENT, 150 H.P., 450 R.P.M.
by the Oerlikon Machine Works, Zurich,
TAKING 150 AMPERES AT 750 VOLTS
SLOT
½ Size
Scale 1 10

FIG. 529.—150 H.P. RAILWAY MOTOR. (Oerlikon Co.)

in generators. Also what high magnetic and electric densities are allowed.

Fig. 529 gives sections of a 150 H.P. railway motor constructed by the Oerlikon Machine Works. It is designed for 450 revolutions per minute on a supply at 750 volts. The armature has 49 slots, receiving 49 former-wound coils, each coil containing 12 wires 140 mils in diameter, covered to 150 mils. The slots are 1·615 inch deep and 0·59 inch wide. The armature wires are two in parallel, so that the 24 wires in each slot will be reckoned as 12 "conductors." Each of the 4 poles receives a coil of 63 turns in series, each turn being two wires in parallel of a diameter of 0·276.

Gearless Railway Motor 117 *H.P.*—The British Thomson-Houston Co. supplied to the Central London Railway several

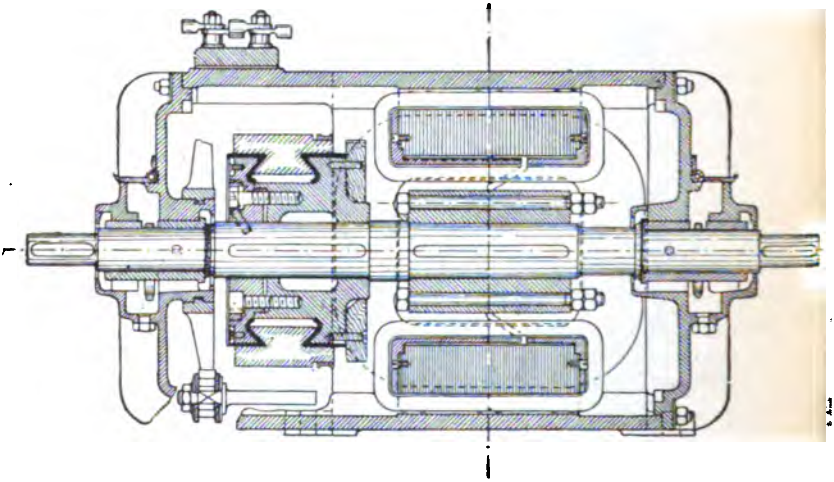


FIG. 530.—ENCLOSED MOTOR OF OERLIKON CO., 12 H.P. at 800 *r.p.m.*

gearless motors of the type R M 4—117—183, taking 192 amperes at 500 volts at normal full-load. These are described by Parshall and Hobart (*Electric Generators*, p. 256), but have since been superseded by single-reduction motors rated at 130 H.P. Each motor armature has 39 slots, with 10 conductors per slot. The armature is ventilated through the shaft, which is hollow.

Oerlikon Enclosed Motor.—Figs. 530 and 531 show a recent type of enclosed motor for use on cranes or for coupling to large machine tools. It is rated at 9 to 12 H.P. according to voltage and speed, being designed for 800 revolutions per minute. Pole-cores and casings are of steel cast in one piece. Two only of the poles are wound. The armature is ring-wound.

Siemens and Halske Carriage Motor.—Figs. 532 and 533 illustrate a motor suitable for a narrow gauge tramcar. The same firm has recently constructed light motors of similar type with two commutators for automobiles and postal carts. They have series-parallel control and electric braking. A motor weighing about 440 lb., working at 80 volts, and making 800 revolutions per minute, will drive a car weighing from 1 to 2 tons at a speed of 10 to 15 miles per hour.

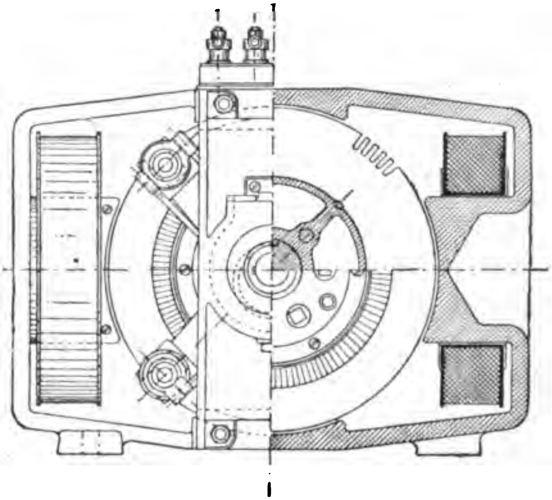


FIG. 531.—TRANSVERSE SECTION OF OERLIKON ENCLOSED MOTOR.

A very compact automobile bipolar motor of about 4 H.P., constructed for M. Jeantaud by the Postel-Vinay Co., is described in *Traction and Transmission*, of July 1902, p. 185.

Thury Railway Motor, R M 6—125—525.—Figs 534 to 536 show a 6-pole steel motor by La Compagnie de l'Industrie Électrique, Geneva. These motors were constructed for the rack locomotives of the Aigle-Leysin and Bex-Gryon-Villars mountain railways. Each locomotive is equipped with two motors having single reduction gear. The motors, which are operated in parallel, have an output of 125 H.P., and at 650 volts pressure take a current of 126 amperes; their speed is 525 revolutions per minute. They have six poles of cast-steel with cast-steel yoke; the motors are series-wound, the magnet coils having each 90 turns of 45 square mm. section wire, the six exciting coils being connected in two parallels, there being thus 3 coils in series. The armature has 232 slots, each 21 × 35 mm. In each slot

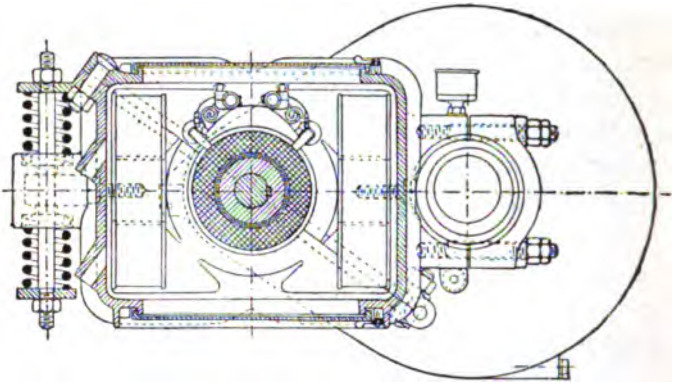


FIG. 532.—SIEMENS AND HALSKE CAR MOTOR.

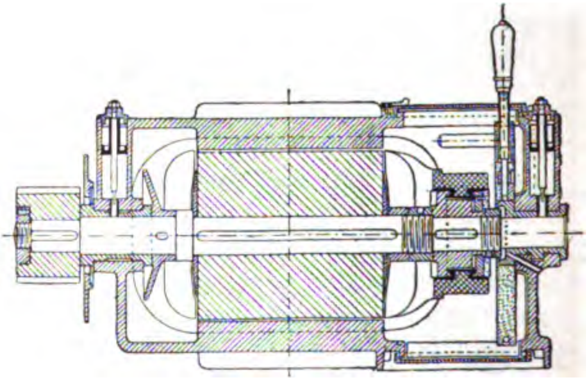


FIG. 533.—SIEMENS AND HALSKE CAR MOTOR: LONGITUDINAL SECTION.

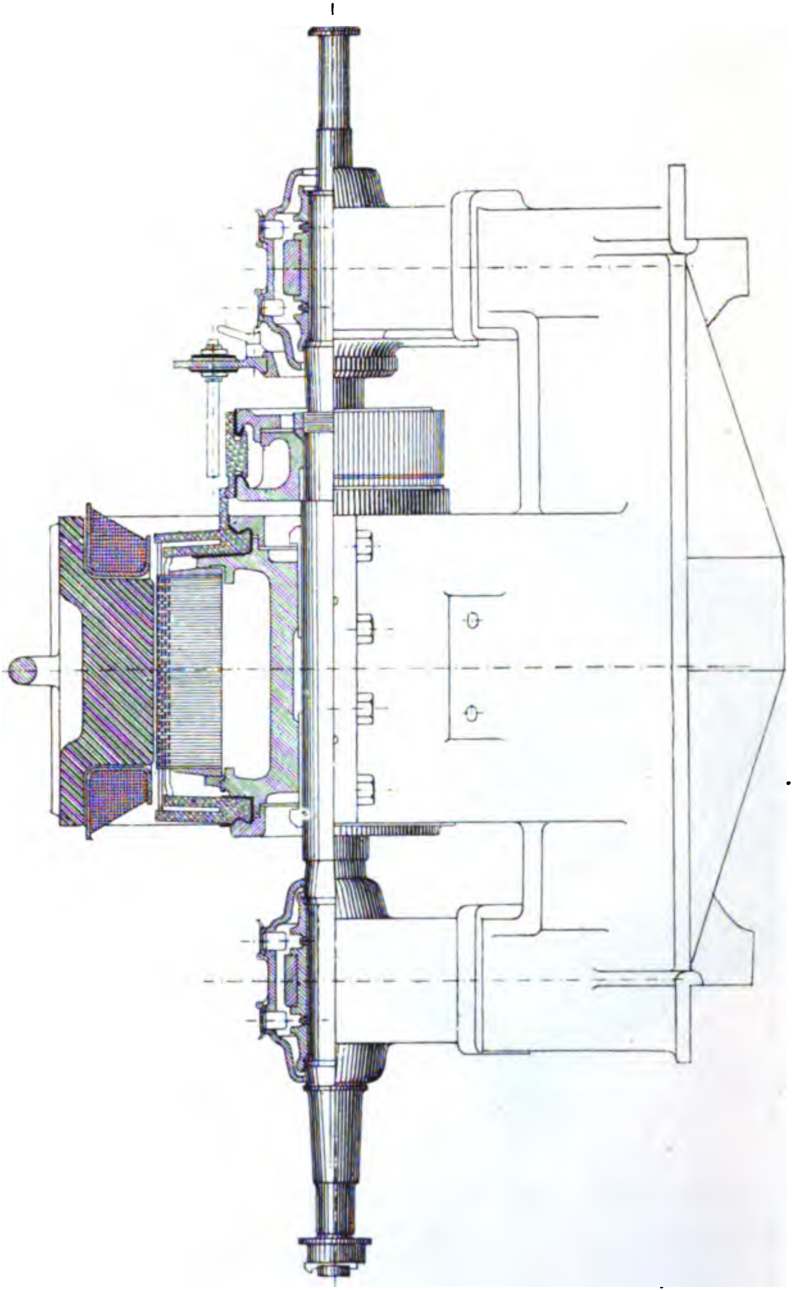


Fig. 534.—Thury's 6-Pole Motor for Mountain Railways: Longitudinal Section. (Scale 1 : 12.)

there are two conductors of 15 square mm. section. The commutator has a diameter of 350 mm., and has 232 segments. The armature core is of diameter 570 mm., and

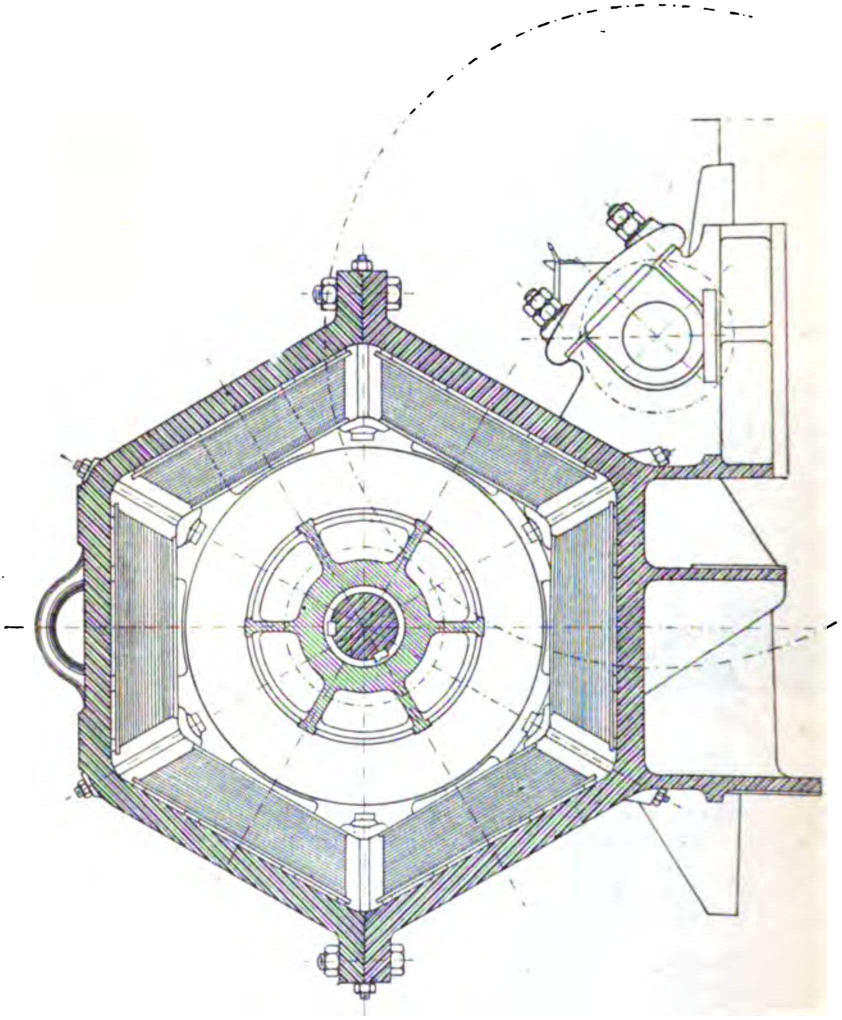


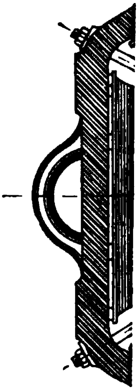
FIG. 535.—THURY'S 6-POLE MOTOR FOR MOUNTAIN RAILWAYS: TRANSVERSE SECTION. (Scale 1 : 10.)

310 mm. length. The shaft is 105 mm. in diameter. The pole section is 155 × 300 square mm.

Plate XXIX. depicts a Thury motor V M 4—15—600.

FIG. 536.—THURY'S 6-POLE STEEL MOTOR, 125 H.P., FOR MOUNTAIN RAILWAYS.

the
cor
me



31
po

This motor is completely enclosed and is designed to run on a vertical axis. It was constructed for the Russian cruiser "Gromoboi"; its output is 15 H.P. at 600 revolutions per minute, at a pressure of 100 volts; thus taking 138 amperes

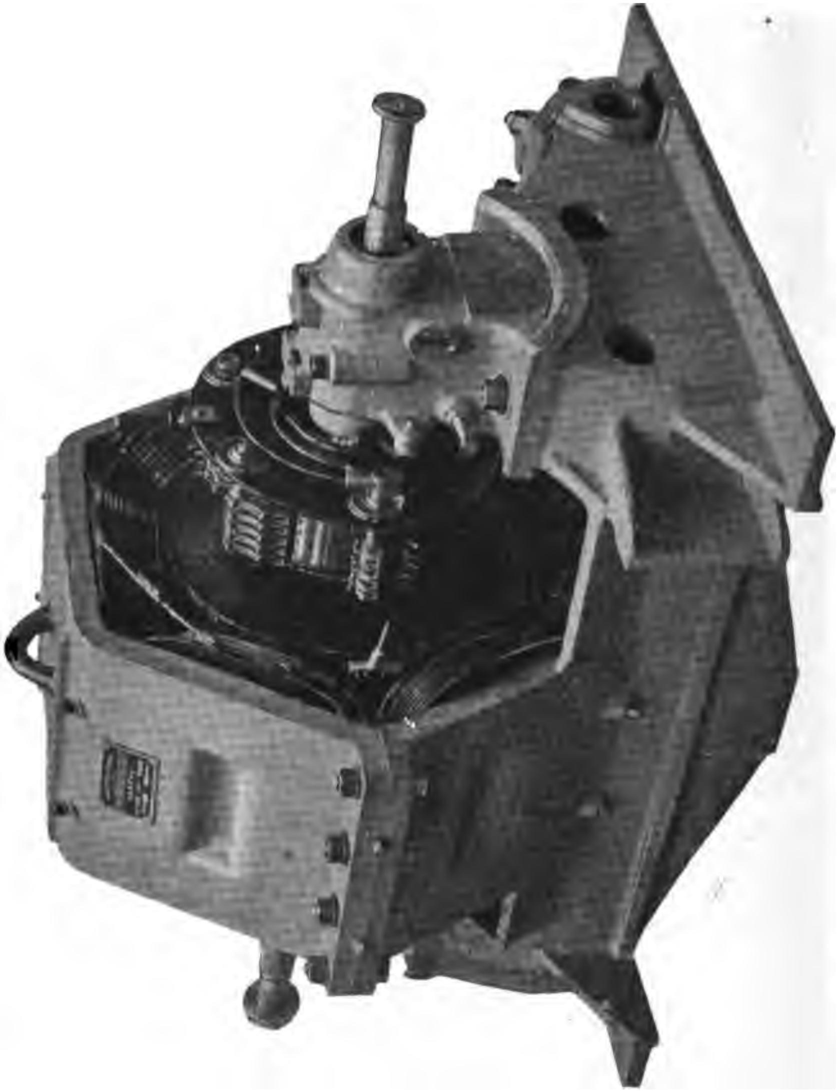


FIG. 536.—THURY'S 6-POLE STEEL MOTOR, 125 H.P., FOR MOUNTAIN RAILWAYS.

at full-load. There are four laminated poles slightly rounded at the pole tips, and fixed by means of a rivet and two screws to the carcass, which is an ordinary casting. The machine is shunt-wound, each field coil being wound with about 1050 turns of wire of 1·76 sq. mm. section, the total resistance of the four coils being 28·9 ohms at 28 deg. C. The armature has 113 slots 5 mm. wide and 18 mm. in depth, there being in each slot two conductors of 19 square mm. section. The total resistance of the armature is 0·065 ohm at 28 deg. C. Each slot contains two conductors having a section of about 19 square mm.; the ends being connected together by means of evolute connexions of 25 square mm. section. The commutator is 180 mm. in diameter and has 113 segments.

CHAPTER XXVI.

REGULATORS, RHEOSTATS, CONTROLLERS AND STARTERS.

Regulators for Dynamos.—Modes of governing the performance of dynamos are needed, not only for keeping the pressure at some constant number of volts or for keeping current at some constant number of amperes, but also for such purposes as to enable the voltage of any one dynamo to be raised in order that it may feed into some distant point of a distributing network.

The voltage of a dynamo depends on three intrinsic matters namely (i.) speed n, (ii.) number of armature conductors Z, and (iii.) magnetic flux **N**; and on two extrinsic matters, namely (iv.) resistance of the circuit, and (v.) counter electromotive-forces in the circuit. It is therefore clear that any one of these five matters might afford a method of controlling the performance of the machine.

To introduce resistance into the main circuit is always wasteful, and may be dismissed as an uneconomical method of regulation suitable only for experimental purposes. To introduce counter electromotive-forces into the external circuit can be done in the case of alternate currents by the use of choking coils, and in the case of continuous currents by the reversed introduction of charged secondary cells; but this is impracticable save for special cases on the small scale. It remains therefore to consider the three intrinsic methods.

Governing the voltage by changing the speed is clearly limited to those cases where there is a separate engine for each dynamo; and in such cases a special governor will be required instead of the usual centrifugal engine governor.

To alter the number of conductors in a rotating armature whilst it is running is absurd. Their *effective* number can, however, in some cases be altered by the device of shifting forward the brushes so that they collect the current not at the point of highest potential, but at some other point. This method virtually uses some of the armature windings, namely, those between the neutral point and the point to which the collecting brush is advanced, to produce internal counter electromotive-forces.

To alter the magnetic flux is the almost universal mode of control; and it may be accomplished in two entirely distinct ways. Since the flux depends on the excitation (or ampere-turns) and on the reluctance of the magnetic circuit, it can be varied by varying either the former or the latter. The excitation may be altered in various ways, (*a*) by rheostats or controllers in the exciting circuit, or (*b*) by altering the exciting voltage, or (*c*) by altering the number or grouping of the exciting coils. The magnetic circuit may be varied in several ways, as (*d*) by moving the pole-pieces nearer to or further from the armature, (*e*) by opening or closing some other gap in the magnetic circuit, (*f*) by drawing the armature end-wise from between the pole-pieces, (*g*) by shunting some of the magnetic lines away from the armature by applying a magnetic shunt across the limbs. All these magnetic devices have been tried,[1] but not with much success except in small machines.

Regulating Rheostats.—A rheostat consists of a set of easily adjustable resistances. These resistances are usually so arranged that they can be introduced into or cut out from a circuit in a regular succession of operations performed by the movement of a switch over a number of contact points. The method of regulating the voltage of a shunt dynamo (or separately-excited dynamo) by inserting resistance into or removing it from the exciting circuit was described on page 306, Fig 172. In the case of a series dynamo the regulation is effected by applying a rheostat to shunt the magnetizing coils.

---

[1] For an example of (*d*) see Firth's method (see *Industries*, ix. 161), in which the polar masses are drawn backwards by screws; and of (*g*) a magnetic shunt applied by Desroziers, *La Lumière Électrique*, xxiv. 394. Other magnetic methods have been used by Goolden and Trotter, Langley, P. Müller, Lontin and Diehl. The latest examples are those of Hundt (see *Elektrot. Zeitschrift*, xxiii. 235, and Couffinhal (see *Bull. Soc. Internationale*, 1903). The very same means here enumerated for governing the *voltage* of *generators* are available for regulating the *speed* of *motors*.

The rheostats needed for regulating shunt-dynamos require to be able to carry, without overheating when in continuous use, the exciting current. They ought to be made of German silver, rheostene, or some such alloy the resistance of which does not vary much with rise of temperature. They must be designed to have a sufficiently great total resistance to reduce the exciting current to the minimum required for the lowest voltage. They must also be subdivided, with a sufficiently large number of contact points to permit of their resistance being introduced by steps with a sufficient and regular gradation. Lastly they. must be properly ventilated and protected.

AUTOMATIC REGULATORS FOR CONSTANT PRESSURE AND CONSTANT CURRENT.

In all automatic regulators there is a part which has to act as the brain of the instrument, watching as it were against any variation, and setting into action the mechanism which is to counteract the variation. This watching device is usually some sort of an electromagnet, often a coil with a movable plunger. When the volts are to be kept constant the coil of the controlling device must be wound as a voltmeter coil, that is of fine wire, of high resistance, and connected as a shunt across the mains. When the amperes are to be kept constant the controlling coil must be wound like an amperemeter with thick wire, of low resistance, and inserted in the main circuit. Alternators are usually regulated by operating on the circuit of their exciters, the current in the governor coil being derived from the mains by a small transformer.

Automatic regulators are of two species: in one the work of moving the regulator is accomplished mechanically, the control only being electrical; in the other both the control and the moving power are obtained electrically. Goolden's regulator, which was illustrated in the previous edition of this book, belongs to the former of these classes. The sliding piece of the rheostat is worked by a vertical screw, and this is caused to rotate right- or left-handedly as may be required under the operation of a double crown-wheel on a sleeve on the vertical spindle to which rotation is imparted by a small pulley driven slowly from the engine. The controlling part —the brain of the apparatus—is a solenoid with suspended iron plunger. When the current in this coil is of proper normal strength the plunger is drawn in just so far that the crown-wheel is not in gear either with the upper or the lower driver. If the current in the coil grows weak the plunger rises, causing the crown-wheel to engage in the upper driving screw, which immediately begins to move the sliding-contact

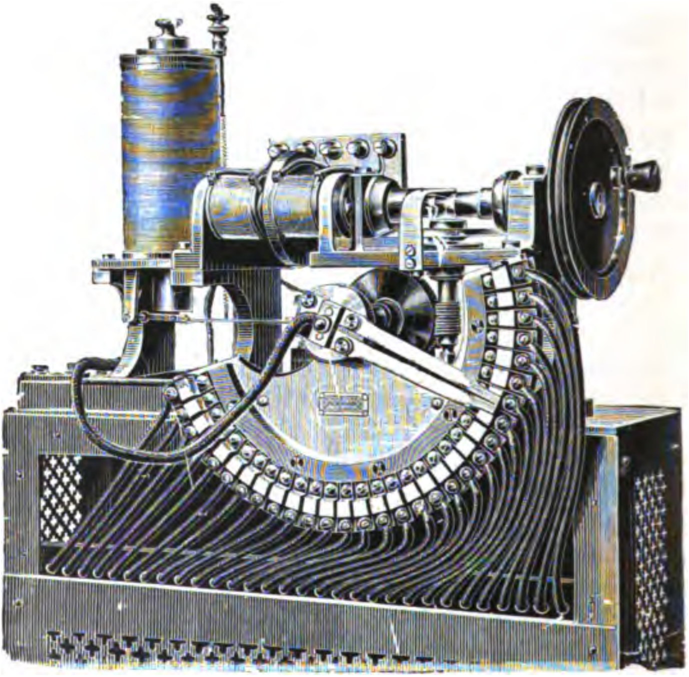


FIG. 537.—THURY'S REGULATOR.

in such a way as to increase the excitation of the dynamo, and bring back the current in the coil to its normal strength. Slater Lewis introduced a differential solenoid arrangement into the regulator.

In Fig. 537 is shown an automatic regulator of the first kind, designed by Thury, and manufactured by the Allgemeine Co., of Berlin. The vertical relay is shown on the left: it actuates one or other of two horizontal coils which throw into gear one or other of the two bevel wheels that drive the worm which turns the rheostat arm. The pulley on the end of the driving shaft must be driven slowly from the engine; or in emergency may be turned by hand.

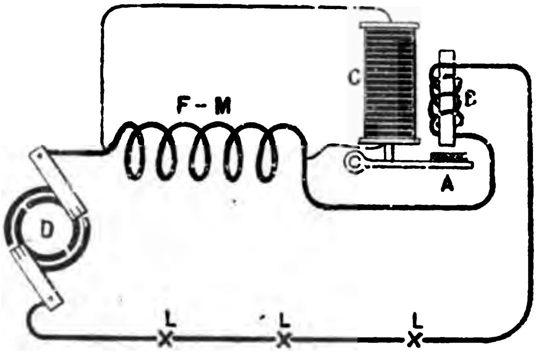


FIG. 538.—BRUSH'S AUTOMATIC REGULATOR.

A simple example of the purely electric regulator is afforded by that of Brush (Fig. 538) by which a series dynamo is made to yield a constant current. Across the field-magnets F M is connected a carbon shunt C of variable resistance, the resistance of the shunt being adjusted automatically by a governing electromagnet B whose coils form part of the main circuit.

When traversed by the normal current it attracts its armature A with a certain force just sufficient to keep it in its neutral position. If the current increases, the armature is drawn upwards and causes a lever to compress the column of carbon plates; the current thus being diverted to a greater or lesser extent from the field-magnets. This regulator will keep the current constant even though the speed of driving may be irregular.

Another purely electrical regulator is that used with the Thomson-Houston arc-light dynamo (p. 747).

A regulator devised by Waterhouse employs a third brush upon the commutator to carry a variable portion of the current around a special circuit. It was illustrated in the previous edition of this book, as were also the regulators of Henrion and of Sperry.

A special study of this method of regulation has been made by Caldwell,[1] who has shown that it can also be applied to constant-pressure regulation.

For constant-current work Wood has devised a regulator in which a pilot brush is also employed, but there are two exciting circuits wound differentially, and there is an electro-mechanical device for shifting the brushes, attached to the dynamo. It was depicted in the former edition.

An interesting example of the use of a magnetic shunt to produce a constant current, occurs in the regulator of Trotter[2] and Ravenshaw, in which, instead of diverting the magnetic lines out of their usual path into a path of lower magnetic reluctance by employing a movable keeper of iron, the plan is adopted of fixing the keeper and varying its effect by surrounding it with a counter magnetizing coil.

M. Reignier[3] has drawn attention to a solution of the problem of exact governing to procure a constant current by automatically varying the number of coils through which the current is permitted to pass.

MOTOR STARTERS.

When a continuous-current motor is started, resistance must be put in series with the armature because as there is no back electro-motive force to counteract the applied voltage of the line, the switching of the latter straight on to the small resistance of the motor itself, would result in an abnormal rush of current. This, besides being bad from an economical point of view, and productive of a drop of voltage on the mains, would prove injurious to all but the smallest motors. Therefore, with motors above about 2 H.P., it is usual to use *starters.* A starter consists essentially of a suitable resistance to be inserted at starting to reduce the initial rush of current, and which can be cut out in sections by successive movements of a handle as the motor gets up speed.

---

[1] *Electrician*, xxii. 217, 1888; and remarks by Professor Nicholls, *ibid.*, 441, 1889.

[2] See paper by A. P. Trotter, in *Electrician*, xix. 374, 1887. A drawing of the governor itself is given in the *Electrical Review*, xix. 289, Sept. 17, 1886.

[3] *La Lumière Électrique*, xxvi. 420, 1887.

When the starter is first put on, it allows a current of say 30 per cent. more than the normal full-load current to flow ; and a correspondingly greater torque than the full-load value is exerted. The motor starts rotating and a back electromotive force is set up, which, as the speed rises, gradually reduces the current. With this reduction of current, the torque is reduced and the motor does not increase in speed as fast as it did when first started. When the current has been reduced to a certain value, the regulating handle is moved on round to the next contact and some resistance is cut out, and current and torque both rise accordingly. As the induced electromotive-force depends on the magnetism of the field-magnets, it is important that these should be strongly magnetized from the first. In the particular case of shunt motors, the starter is usually arranged to switch on the exciting circuit before any current is allowed to pass into the armature.

Most starters, besides having the ordinary arrangements for cutting out resistances, are provided with devices automatically to disconnect the motor from the mains, if the supply should for any reason fail, or, if the field connexions are broken at any time, or again, if the motor should become unduly overloaded. The first device is shown in Fig. 539. The current on its way to the magnet windings is taken round the coil at A, so that when the switch arm is moved to the full "on" position, it is held there against a spring through the soft iron armature B, completing a magnetic circuit with the projecting iron cheeks of the electro-magnet A. Should current fail to pass through the exciting circuit, owing to failure of supply or to a break in the field circuit itself, the electro-magnet A no longer attracts the armature B, and the spring pulls the switch arm back to the "off" position. The armature is thus protected from the abnormal rush of current which might occur either in consequence of having no field, or at the moment when supply is renewed.

The other device for cutting out the motor when it is excessively overloaded has various forms. In medium-sized motors it takes the form shown in Fig. 540.

The main motor current passes round the coil C, and if an excessive current is flowing, the armature D is attracted to the pole-piece E, and thus the metal at F makes an electrical connexion between M and N, which are connected to the terminals of the no-voltage electro-magnet at A in Fig. 539. No current will pass through the coil A when it is short-circuited, and therefore switch arm will fly off. By means of a screw adjustment, the device may be set for various conditions of overload; for the further away the armature is from the pole-piece, the larger the current will be which is required to move it.

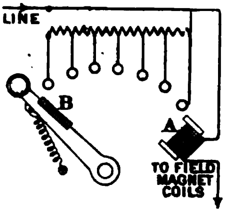


FIG. 539.—MOTOR STARTER: NO-LOAD RELEASE.

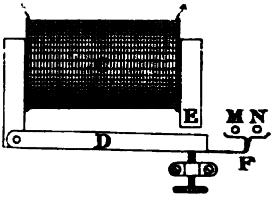


FIG. 540.—MOTOR OVERLOAD RELEASE.

For motors of large size, this device is replaced by an automatic circuit-breaker in the main circuit. Instead of a circuit-breaker, some engineers prefer a fuse for overload protection, as a fuse takes into account the time an overload is on and will not break the circuit for a purely momentary increase of current. A circuit-breaker is set at a certain maximum current, and when that current is reached, the circuit is then broken. Because of this, the breaker is generally set for a higher current than allowable, so that momentary rushes of current do not stop the motor.

Fig. 541 is a motor-starter of the British Thomson-Houston Co., furnished with no-voltage and overload release devices.

Besides the safety devices described above to protect the motor when running, some starters have other devices which protect the motor while it is being started up. If the motor has only the arrangements described up till now, there is nothing except the instructions, to prevent an unskilled person from putting the switch arm quickly right round to the full "on" position and holding it there until the overload cut-out is out of action. If a breaker or a fuse were used the breaker could be held in, but the fuse would blow, and the same unskilled person would be induced to put in a heavier one, which is undesirable.

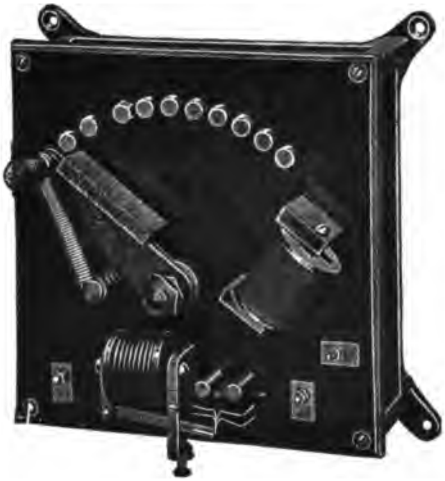


FIG. 541.—MOTOR STARTER WITH RELEASE DEVICES.

A device used by the Sturtevant Engineering Co., is to have the actual handle used for starting on the end of a spindle which gears by a worm thread on the switch-arm, so that when the handle is being turned at the fastest possible rate, the switch-arm is moving round at a moderate speed only. When the switch-arm has been moved round to the full "on" position, it is free to fly back if the current fails.

Another arrangement, is to have a switch-arm separate from the contact-arm, the two being electromagnetically connected together by a coil, which is placed in the circuit in a similar position to the no-volt coil. When the main switch is closed, the switch-arm will move the contact-arm round; and if it is moved round too fast, the overload cut-out actuates and short-circuits the coil on the starting arms and the contact arm flies back to the starting position. When the starter is enclosed in a case with only the starting handle outside, it then becomes "fool-proof."

The Sturtevant Co. has also a special starter for motors above 50 H.P., consisting of a number of switches placed side by side; and, when starting up, interlocking devices allow only one switch to be closed at a time, and that only in its right turn. In case of overload or failure of current, all switches are opened simultaneously.

Provisions for Stopping Violent Sparking on Switching Off.—When the motor is being cut out because of over-load, arcing will occur on the contacts, especially on the last one where the current is finally broken. Because of this, most firms so design the contacts for starters of large motors that they are easily renewable.

To minimise flashing at the final break, the first two contacts are usually dummies, i.e. there is no connexion from them to the outside circuit, so that the final flash is spread over the distance between 2 or 3 contacts. The British Thomson-Houston Co. makes use in some patterns of starters of the well-known magnetic blow-out device, by means of which the final arc occurs between the poles of an electromagnet

Special Precautions with Shunt Motors.—With shunt motors, because of the large self-induction of the shunt windings, account has to be taken of the following points:—(i.) that in switching on the field-magnet, the current may take an appreciable time to grow to its normal value; (ii.) that in switching off, especially with quick-break switches, high voltages are induced in the windings, and may do damage to the insulation. To meet the first point, the field connexions are generally separated from the actual starter, and taken to the main switch, so that whenever the main switch is closed the current flows through the field coils. To meet the second point it is usual, at least for shunt motors of small and moderate size, to unite the armature and field-magnet circuits in a closed circuit that is never opened. The connexion with the mains is introduced as in Fig. 542, so that on switching off the field-magnet, discharge can find a closed path through the armature. In other cases, in order that rises of potential may not injure the insulation when the shunt is opened, a special form of main switch is sometimes used which, before breaking from the supply, puts a non-inductive resistance across the shunt of the motor. This is known as a "flashing" resistance, and is, in practice, of about the same number of ohms as the shunt which it protects.

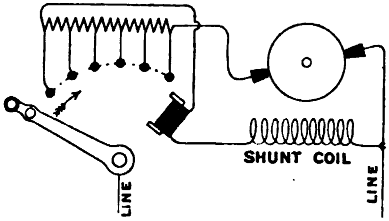


FIG. 542.—SHUNT MOTOR CONNEXIONS.

Motor Regulators.—Up to now we have been describing starters pure and simple, which only allow for the motor being started up, and then to run at a constant speed. As we have seen, there are two ways of obtaining a variation of speed in shunt motors, viz., by altering the value of the exciting current, or by putting resistance in series with the armature.

If the first method is used, the ordinary starter may be used in conjunction with a separate regulating rheostat for field excitation. When the second method is used, the design of the starter is modified so that it will serve the double purpose of starting and regulating the motor. The design of the resistances has, however, to be modified (1) so that the whole current can be carried for long periods; (2), the no-voltage cut-out has to be modified because it must now hold the switch-arm on and release it at any contact. The modified arrangement generally used is indicated in Fig. 543. When the electromagnet G is excited, the armature is attracted and H is held in the notches in W, and thus the switch-arm is held in any position. When current in G fails, H drops and the switch-arm is free to fly back to the "off" position. An over-load cut-out may actuate this no-voltage device, just as with the other form.

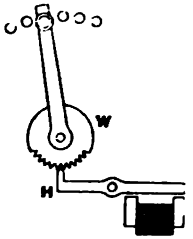


FIG. 543.—MOTOR REGULATOR AUTOMATIC RELEASE.

Arrangements for Reversing the Direction of Rotation in Motors.—To reverse the direction of rotation of a continuous-current motor, either the armature or the field must be reversed, but not both.

The reversing of the armature is, of course, the only practical way, as the field should never be broken when the supply is on.

If the pattern of starter already described were used, it would be necessary to have two rheostats, one for starting in one direction, the other for starting in the reverse direction. To enable one set of resistances to suffice, a special form of reversing regulator has been devised which is shown diagrammatically in Fig. 544.

There are two sets of contacts, above and below the centre-line; and there is also an inside contact in the form of a split ring, the two halves corresponding to the two sets of contacts. There are two contact-pieces used, one for the top half of the regulator and the other for the bottom half. These contact-pieces thus make contact between A or B and the contact studs on the top or bottom half of the regulator, and are both attached to the same switch-arm but insulated from it. The central pieces are connected to the armature, and the top contacts are connected to the bottom contacts as shown.

The action for reversing is as follows:—When the switch-arm is moved from the "off" position so that contact pieces make contact in X and Z quadrants, the current will flow thus C D X A B Z Y and out; and when the contacts in the Y and W quadrants are being used, current will then flow thus C D X W B A Y and away. Thus it is seen that each time

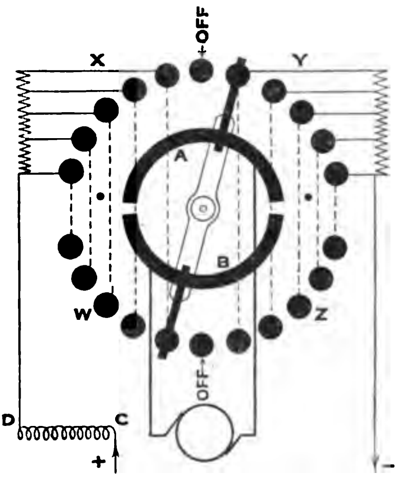


FIG. 544.—MOTOR REVERSING REGULATOR.

the current flowed in the same direction through the field-magnet coils C D, but it was reversed through the armature A B.

The diagram shows the case of a series motor, but the same regulator will do for a shunt motor, the magnet-coils being connected directly across the mains, as in Fig. 546.

BRAKING.

In some cases of motor installation it is required to stop the machinery quickly, and this may be done, (1) by causing the motor to act as a generator and convert the energy stored in the moving parts into electrical energy which is either returned to the line or absorbed in resistance; or (2) by means of an electro-magnetic device which automatically puts a brake on a pulley fixed on the shaft of the motor when current is cut off from motor.

Electrical Braking.—(1) The case of *series* motors. To cause a series motor to act as a generator it must be disconnected from the line entirely and the field-magnet connexions

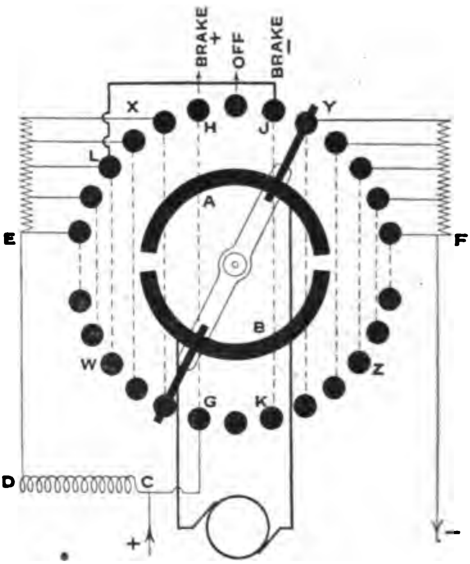


FIG. 545.—MOTOR REVERSING REGULATOR WITH BRAKING CONNEXIONS.

must be reversed with respect to the armature. The reason for reversing the field-magnet connexions is that with the residual magnetism, the armature will start to generate current in an opposite direction from that in which it was being supplied when last connected to mains, and if the connexions are not now reversed, this current, instead of building up the magnetism, will demagnetize the machine.

The controller shown in Fig. 544 above, is in Fig. 545 adapted for braking purposes in a series motor by the addition of four extra contacts G, H, J and K, as shown on either side of the off positions of the top and bottom sets of contacts. These contacts are cross-connected as shown and one pair is connected to the resistances on the *opposite* side of the off position as J L, while the other set is connected to the line end of the field as shown.

Assume the motor is running with contact pieces in W and Y quadrants, the current will flow thus, C D E X W B A Y F and out. Now, bringing the arm back to the position for braking, i.e. to contacts G and J, the current will then flow,

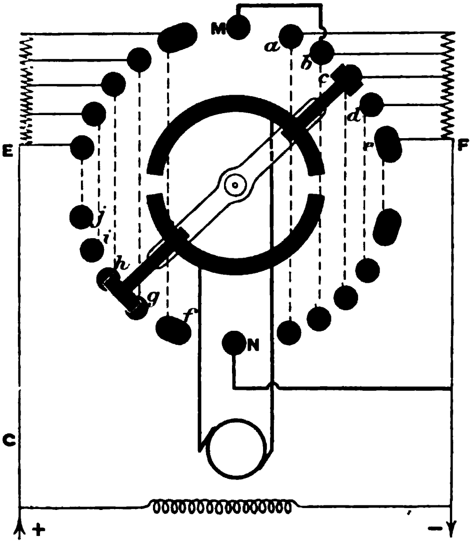


FIG: 546.

taking it through field-magnet coils in the same direction as before C D E L J A B G and back to C. The direction through armature is thus reversed although it is the same through C D.

(2) *The Case of Shunt Motors.*—In shunt motors, the current in field coils is independent of the current in armature, so to brake with a shunt motor, the armature alone is disconnected from the line and short-circuited through a resistance.

In some cases with shunt motors, energy can be returned to the line. For a given current in the magnet coils, a shunt motor will run at a given constant speed. If the speed of the motor is caused to exceed this natural limit, a higher back E.M.F. will be generated than the applied E.M.F. of line, and current will be returned to line. This last method of braking is used on tramway systems where long gradients occur and, of course, has the double advantage of returning energy to the line and keeping the speed of car down to the ordinary schedule speed.

In Fig. 546 is shown the same type of regulator already dealt with, adapted for braking with shunt motors. In this case, the same contacts M and N as before used as dummies in off position are used for braking. One of them is connected to the one side of supply and the other is connected to a point in the resistances on the same side as shown. A main switch closes the shunt circuit, which is not broken again until the motor is at rest. The motor can, therefore, when switch is in off position generate current which passes through the resistances.

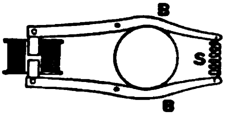


Fig. 547.—Electro-magnetic Brake for Motor.

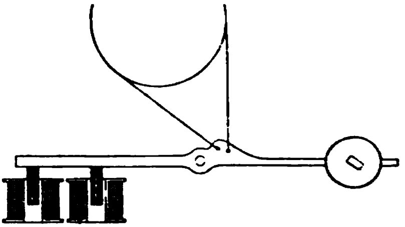


Fig. 548.—Electro-magnetic Band Brake.

(The special arrangement of the contact studs in this diagram serves a special purpose, which is hereafter described, p. 911, and has nothing to do with braking operations.)

Mechanical Brakes, actuated by electromagnetic devices.

A simple arrangement for an electromagnetic brake is shown in the accompanying Fig. 547.

When the motor is disconnected from the mains the spring holds the brake blocks B B fast down on the pulley, but when motor is switched on, current flows through the solenoid and the iron cores are pulled in so that the brake is released. By taking leads from the ends of the coil to push-buttons at different parts of the machine, the coil may be short-circuited and the machinery stopped.

The next cut, Fig. 548, shows a brake for a larger machine. It was used, in fact, on a large Hoe printing machine at the Glasgow Exhibition. The principle is the same as before, but the various modifications tend to make the brake much more powerful.

CONTROLLERS.

A controller is a species of switch in which a number of operations of changing connexions are performed in the simplest way by the rotation of a cylinder which bears upon its periphery a number of insulated contact-pieces arranged to make contact between different arms or wipers that are the terminals of various parts of the circuit. Very simple controllers for performing such operations as reversing a current or joining a group of battery cells in series or parallel have been known for many years, having apparently been invented by Reusch in 1854. In recent years the controller has been much developed in its application to the use of motors, particularly tramway motors. Many of the modern forms are highly complicated. It will be expedient therefore to explain the simple operations which controllers effect, rather than to attempt to describe any of the detailed forms now in the market. Any one who follows out these simple forms can readily identify the purposes of the various parts of a complicated controller. Controllers can be arranged to perform the following operations :—

1. Switching on and off.
2. Introducing a resistance, and cutting it out in successive steps.
3. Putting two machines (two coils, two armatures or two batteries) first in series and then subsequently in parallel.
4. Reversing.
5. Electrically braking.
6. Shunting an exciting coil to weaken a field-magnet

We will take these operations in order.

Operation 1. *Switching on the Current.*—The method of switching on the current is indicated in Fig. 549. In this figure the shaded areas A and B represent contact-tongues or wipers, and the white area to the right represents a contact piece on the controller drum. It is here shown as a flat area, but must be imagined as curved around the surface of the drum. The wiper A is directly connected to the line, and wiper B goes to the motor through the starting resistance. When the drum is turned so that both wipers touch the contact-piece an electrical connexion is made between A and B.

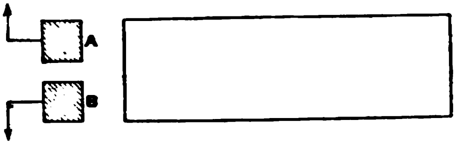


FIG. 549.—CONTROLLER. OPERATION OF SWITCHING ON.

Operation 2. *Inserting and Cutting out Resistance.*—The next set of contacts in a controller are those for cutting out the resistance. Fig. 550 is again drawn flat, while Fig. 551 depicts the controller drum, with the contact-piece upon its surface. The vertical dotted lines in Fig. 550 indicate the successive positions of the contact-piece with respect to the row of contact tongues or wipers. In position 1 the wiper B only makes contact, and in this position the

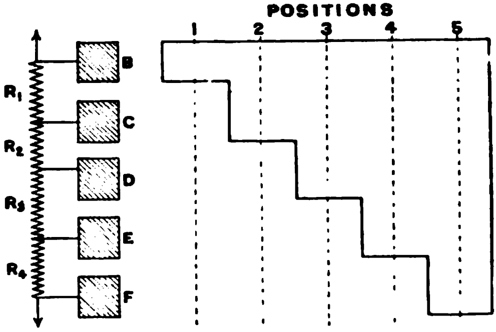


FIG. 550.—CONTROLLER CONTACTS FOR CUTTING OUT RESISTANCE.

current must necessarily pass through all the four resistances. Fig. 551 shows the state of things when the controller drum has been turned to position 2, when wipers B and C both touch against the contact-piece. In this case R_1 is cut out and the current has to traverse R_2 R_3 and R_4 only. When the controller is turned to position 3, R_2 is cut out, leaving R_3 and R_4 in the circuit. In position 5 all resistances are cut out. On turning the drum back the resistances are successively switched in. In Fig 550 the wiper B is actually the same B as in Fig. 549. The contact-piece, with its characteristic "steps," is here drawn as though it were cut out of a thick sheet of metal, and merely fixed on the surface of a drum of wood or other non-conductor. In fact, primitive controllers were so constructed. But in a modern controller it would be built up of a number of separate metallic segmental pieces, mounted on insulating supports upon a central vertical shaft. These segmental pieces have different lengths of arc, and are connected metallically together where a set are required to cut out resistances as described. The reader should compare Fig. 553 and Fig. 559.

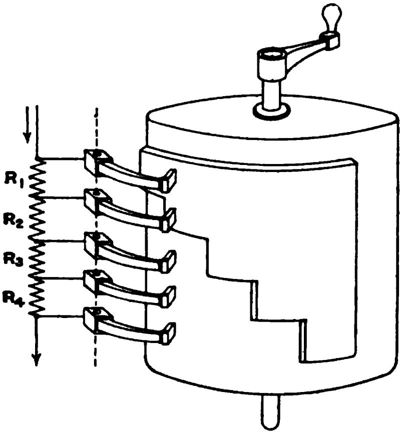


FIG. 551.—DIAGRAM OF CONTROLLER DRUM.

Operation 3. *Putting in Series and Changing to Parallel.*— Fig. 552 shows the parts of the controller for this operation.

After passing through whatever resistance may be in to F, the current goes to G, these two tongues being connected electrically together. When the drum is moved into its first position, a contact-piece connects H and I together, so that current flows from G through the first motor to I, to H, and then through the second motor to J, i.e. to "earth"; on moving the drum to its second notch, these same connexions are kept on, and are in fact used all the while resistance is being cut out. The motors are then put in parallel by the use of the set of contact-pieces shown on the right of the diagram. These contacts connect G and H and also I and J together, so that when the current comes from F it divides, part going through the first motor to earth via I and J, and part going through the second motor to earth via G and H. When the motors are changed to parallel from series, resistance is again inserted in series with them. This is done by repeating the process of Fig. 550 in the positions of controller used for series working. This point is further elucidated by Fig. 553, which represents a complete controller in which the various processes here described are combined.

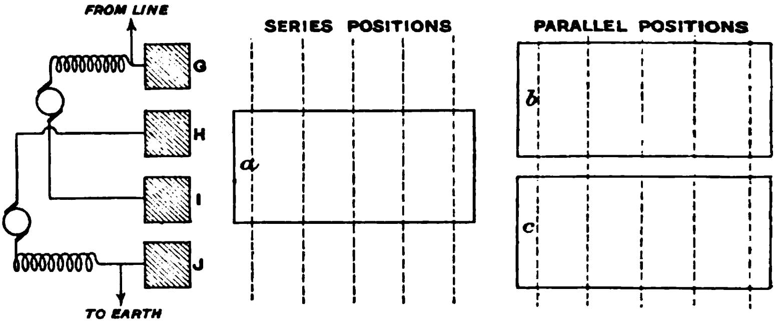


FIG. 552.—CONTACTS FOR CHANGING FROM SERIES TO PARALLEL.

Operation 3a. Series-Parallel Arrangements with a Shunted Field-Coil, for last series and parallel positions, Fig. 554.—This process is effected by the use of two additional contact tongues K and L, which, at the last series and parallel positions, are electrically connected with I and J by means of the extra contact-pieces shown, thus putting the field coils (as $R_{\prime\prime\prime}$) and shunting resistances (as $R_{\prime}$) in parallel with one another. This shows the principle of the method, but as explained later, the arrangements of contact-pieces for series-parallel and coil shunting operations are somewhat modified in the actual controller.

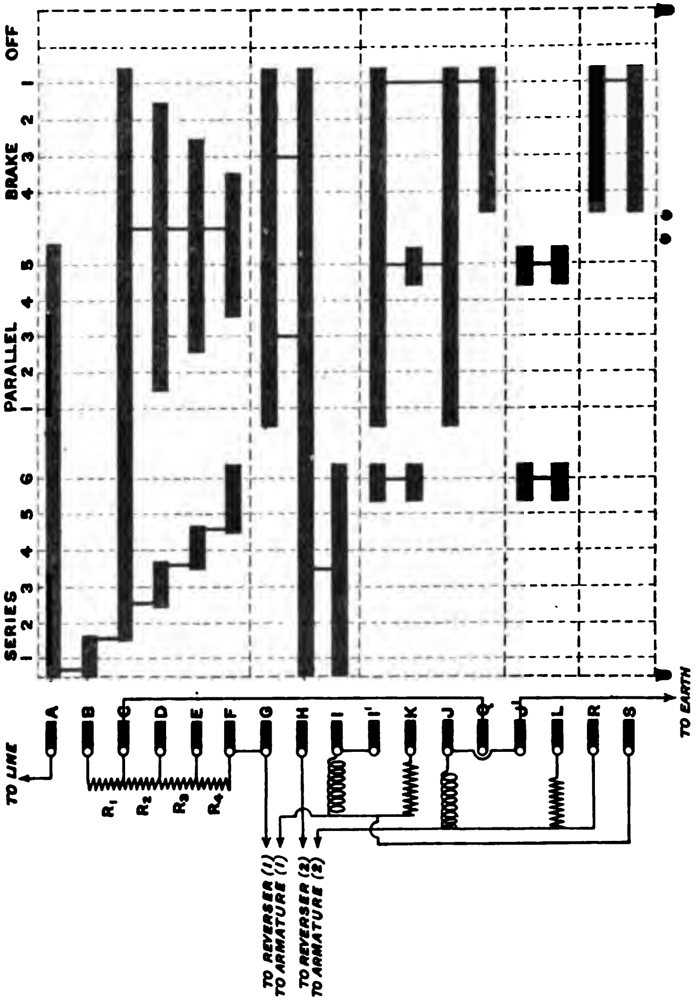


Fig. 553.—Diagram of Complete Controller.

Operation 4. Reversing.—As already explained, to reverse the direction of rotation of a continuous-current motor, the armature connexions are reversed with respect to the field-coil connexions. To do this, a small auxiliary contact-drum is generally arranged, separately from the main controller drum ; and in whichever position it is turned, it is automatically locked by the main drum if the latter is not in the " off " position.

There are two distinct types of reversing controller drums in general use.

The *first* is shown in Fig. 555, where we have one set of four contact tongues connected up as shown to the armature

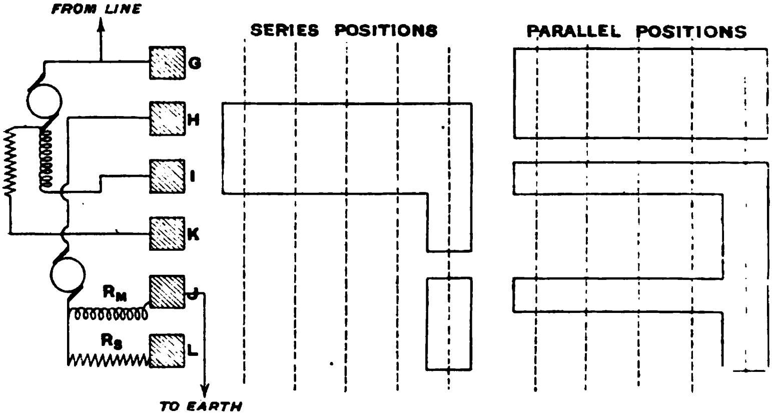


FIG. 554.—DIAGRAM OF OPERATION 3*a*.

and field-magnet coils, the connexions being brought from the wipers G and H in Fig. 553. On the barrel of the controller there are two sets of contact-pieces marked *a b c d* and *e f g h*. The drum is shown in the " off" position. When it is moved to the left, the right-hand set of contact-pieces *a b c d* engage the wipers, and when moved to the right, the left-hand set, *e f g h*, make contact instead. In first case, current passes in at M and then through *a c* O N *b d* P and out through the field coil ; or, in second case, through *f* N O *g h* P and out again, passing through the field coil in the same direction as before, although it has passed in a different direction through the armature.

The *second* arrangement is shown in Fig. 556 and has the advantage that it does away with complicated connexions on the drum itself, although it necessitates the use of a double set of contact tongues. The whole developed surface of the drum is shown by dotted lines and it is supposed to be divided into sections, on one of which the contact-pieces are fixed. As shown, the left-hand wipers will be in contact with the contact-pieces, i.e. will be in position 1, and the right-hand wipers will be in position 3. When the drum is moved one notch to the right, neither set of wipers is in action, this being the "off" position. When the drum is moved one place further round, the right-hand wipers are then in action. In position 1 the current flows in at M^1, and then to N^1 through armature to O^1 and P^1 and out through the field-magnets. In position 3, it will be found that the current goes through the armature in an opposite direction to what it did in 1, but finally traverses the magnet coils in the same direction.

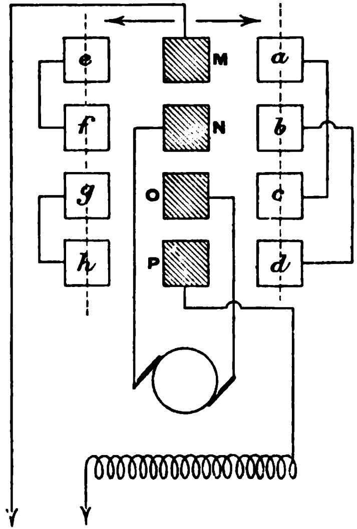


FIG. 555.—DIAGRAM OF REVERSING DRUM.

Combination of Series-Parallel and Reversing Contacts.—When a controller is required for one motor or two motors to be worked in series only, to make it more compact the reversing contacts are generally placed on the main drum, and then, instead of one half being used for series connexions and the other half for parallel connexions, the two halves are used for backwards and forwards rotation of the motors, the central position being the "off" position.

In the more usual case when parallel connexions are also required, the construction is much more complex than the case cited above, because here we have two sets of connexions which are to be put in parallel, viz. the field-coils and the armatures; but only one set viz. the armatures, has to be reversed. This double operation cannot be performed with single sets only of reversing and series-parallel contacts. We must either have two of the former and one of the latter, or *vice versa.* If we have the former, we treat the armature and field of one motor as one, and parallel it as one thing with the armature and field of the other motor (Fig. 557). Then, by means of two sets of reversing contacts, we can reverse the two separate armatures.

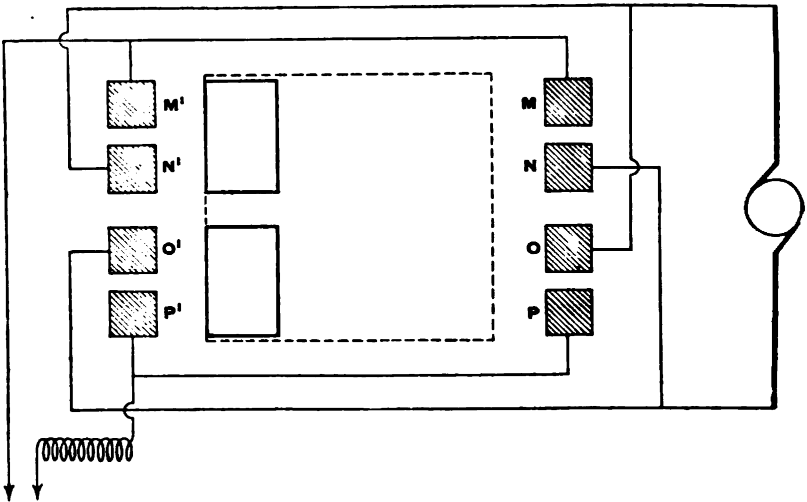


FIG. 556.—REVERSING DRUM (Second Arrangement).

In the alternative method (Fig. 558) we treat the two field-coils as one part and the two armatures as another part. Then the armatures can be reversed as one on one set of reversing contacts, but the fields and armatures have to be paralleled separately on two sets of series-parallel contacts. As the series-parallel contacts have to come on the main drum, the first method is usually adopted and the reversing pillar is provided with two sets of contacts.

Combined Operations in the Controller.—Now that we have seen how the various fundamental operations are performed, we can see how these various processes and arrangements already described are combined and modified in building up a controller.

Afterwards we can see what additions are necessary for electrical braking.

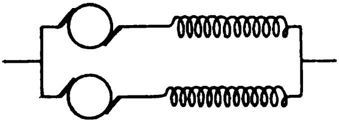


FIG. 557.

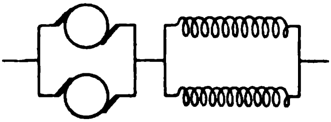


FIG. 558.

The general arrangement of the inside of a controller is shown in Fig. 559, which shows a Westinghouse controller; and it will be seen that where in the previous simple diagrams one large contact-piece was used for a number of wipers as in Fig. 551, in the actual controller, for mechanical reasons, the contact-pieces consist of a number of copper plates (corresponding to the copper wipers) which are electrically connected together by being screwed on to projections from the same cast-iron central drum. Where we have two contact-pieces which must not be electrically together (which are not shown on the simple figures made in one piece), an insulating collar divides the several cast-iron pieces which go to make up the controller drum. These collars are represented by dotted lines in the complete controller drawing; and to make the connexions more clear, those contact-pieces which are built up together are connected by vertical lines.

As a result of this feature of construction, we require, as in Fig. 553, two extra wipers I^1 and J^1, because from Fig. 552 we see that if *a*, *b*, and *c* were built up as represented here, they will all be electrically connected together; for *a* is on a level with the lower part of *b* and the upper part of *c*. By having the extra tongue I^1, the necessary connexion between I and J is made in the parallel positions without making a short-circuit connexion between G and J; which would happen if G and J were electrically connected. For a similar reason we require J^1 for shunting the field-coils of the second motor.

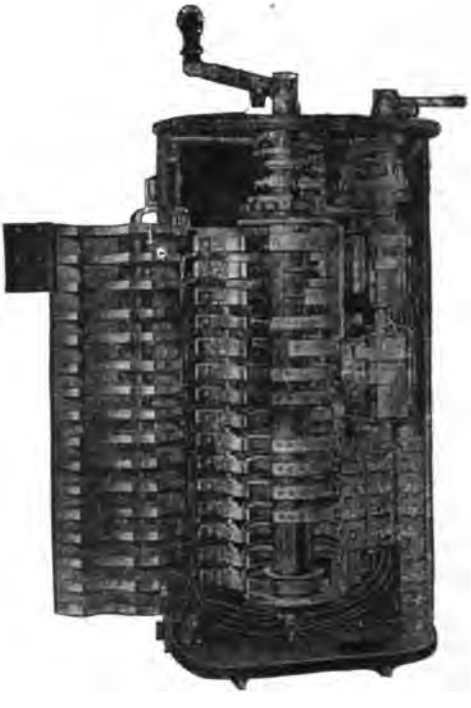


FIG. 559.—CONTROLLER (Westinghouse Pattern).

The following points will also be noticed in the complete controller drawing, Fig. 553.

1. The resistance R$_1$ is only used once, i.e. when first starting up; for when the first parallel notch is reached, the

total resistance in circuit consists only of R_2, R_3, and R_4. The reason for this is that the total resistance at starting is governed by the value of the allowable starting current. which has to be kept fairly low because in tram-car driving the initial acceleration is small, owing to great statical frictional resistance.

When position 6 is reached the car will be running at a good speed, and if, when switching the motors into parallel, all the resistance as in the first position were used, the current should be so reduced that it would probably tend to retard the car rather than accelerate it further. Moreover, as the motors are now running, they can generate a considerable back electromotive-force: and it must also be borne in mind that only half the current from the line now goes through each motor, so that on the first parallel position the current should be greater than the starting current.

2. For the sake of simplicity of construction, those contact-pieces which are brought into use more than once, are, wherever possible, made in one piece, e.g. a contact-piece for *c* is only required in series position 2, parallel position 1 and braking position 1, but one contact-piece is stretched right across for these 3 positions. Note that contact-pieces for D cannot be made in one as R_2 would be cut out in parallel position 1, if this were so.

Operation 5. *Electrical Braking.* — This is obtained by moving the handle from the "off" position in an opposite direction to that which supplies power to the car. At the last parallel position is a stop which prevents any further rotation of the drum in that direction. Therefore, when the motor-man wishes to use the electrical brake, he first brings the handle to the "off" position, thus cutting the current down considerably before the motors are disconnected from the line.

There are five necessary operations for electric braking viz. :—

1. The motors must be entirely disconnected from the trolley-line, and

2. Their field connexions must be reversed.

3. The motors are connected in parallel, and

4. An equalizing connexion is made across their field-coils, as in Fig. 558 (see also p. 928), and then :—

5. The motors are short-circuited through varying amounts of resistance to obtain different degrees of braking.

By reference to the diagram it will be seen that these five operations are performed as follows :—

1. By not having a contact-piece for the first wiper (A) in the braking positions, the current supply is cut off.

2. The reversing of the field connexions may be done by some extra contacts fixed on the bottom of the main drum with connexions similar to those for reversing drums already described. But this method is not generally used as it makes the controller drum unnecessarily long. More generally a separate reversing drum is used, which is turned round, for the braking positions only, by gearing on the main drum. Also sometimes the same reversing drum is used for both reversing and braking, it being reversed independently for the braking position only, in a similar way to that described for the separate reversing drum. The advantage of this separate reversing cylinder for braking is that a smaller number on the main drum are necessary, as seen below. In a controller made by the Brush Co., the extra reversing drum for braking is combined in the main reversing drum, which has therefore 4–8 positions on it. When the motors are to be reversed, the reversing switch turns the drum half-way round, but when braking is required, the main controller drum wound only a quarter.

3. The motors are connected in parallel in just the same way as for parallel running ; and

4. Equalizing connexions can be made by bringing leads from the field-coil terminals, which are not connected to wipers I and J, to two extra wipers R and S, which are connected together in the braking position. This method is only used when the usual reversing contacts are also used in braking. When a separate reversing drum is used, the equalizing connexions are made on this drum by joining together the contacts which correspond to P in Figs. 553 or 555.

5. By the use of another wiper Q, in the same set as I^1 and J, which is electrically connected to C, the motors in the breaking positions are short-circuited on themselves through decreasing amount by resistance.

Other types of Controllers for other Systems of Control.—The *Sprague* type of controller, used by Mr. Sprague for his particular system of control by first putting the field-magnet coils in series and then in parallel is shown diagrammatically in Fig. 560.

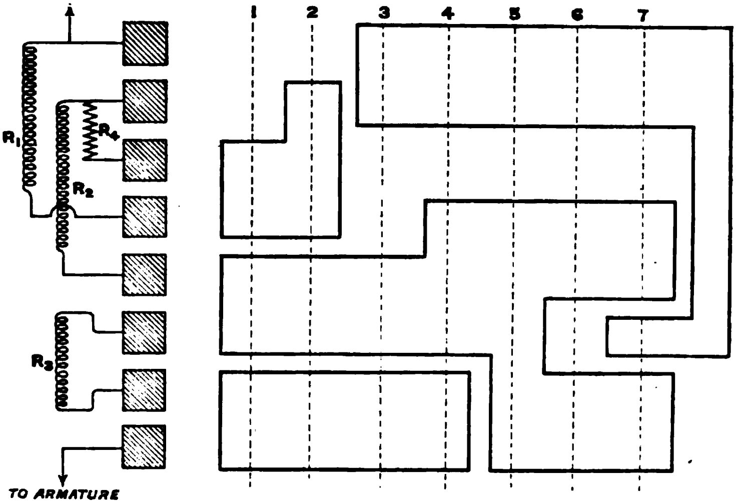


FIG. 560.—SPRAGUE'S CONTROLLER.

In 1st position, it will be seen on tracing out the connexions that R_1 R_2 R_3 and R_4 are all in series.

In 2nd position, R_4 is cut out.

In 3rd position, R_1 is also cut out.

In 4th position, R_1 is put in in parallel with R_2.

In 5th position, R_3 is cut out.

The 6th position is the same as the 5th; and in 7th position, R_1 R_2 and R_3 are all in again but in parallel with one another.

In building up a controller according to this arrangement the mechanical construction would be entirely different from that already explained for the series-parallel controller. The various segments shown must be built up on an insulating cylinder and must not be electrically connected with one another in any way.

Controllers for Shunt Motors.—The main drum for shunt motor control is not essentially different from that for series motor control. Resistance is inserted at starting and is gradually cut out as before. The only difference being that whereas before to get the very highest speeds by shunt the field-coils, in this case resistance is placed in series with them in a similar manner to that in which resistance would be cut out from them, only the building up as it were of the steps is reversed.

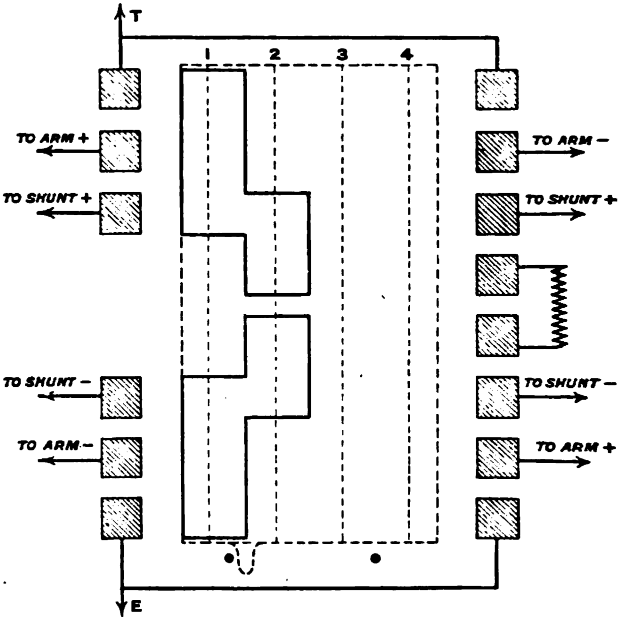


FIG. 561.—REVERSER DRUM FOR SHUNT MOTOR (LAURENCE SCOTT & CO.).

The reverser used with shunt motors is somewhat different from that already described for use with series motors. It serves the double purpose of reversing the armature and making and breaking the field circuit when the power is first switched on to the car or finally switched off.

Fig. 561 shows a shunt motor reverser of the double series of contacts type. There are four positions on the controller drum, and at present the contact tongues are supposed to be on the first and third position, so that current flowing from the line to the armature, goes in at the side marked+. If the drum is now moved one position to right (a stop prevents it from being moved to left) positions 4 and 2 are being used. Now everything has been disconnected from the line and the shunt-circuit is connected across a non-inductive resistance, which should be as great as the shunt itself.

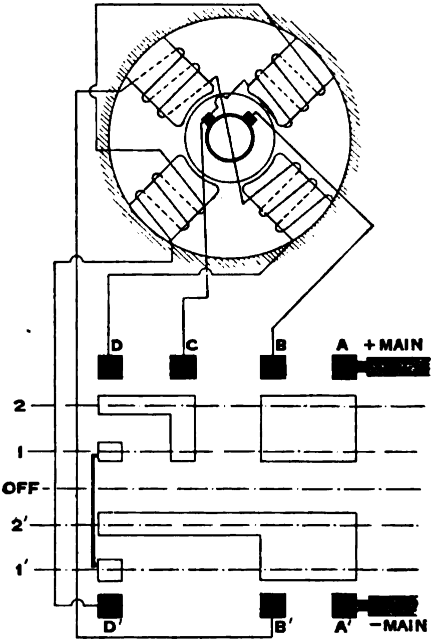


FIG. 562.—MOTOR WITH TWO-SPEED CONTROLLER (LAURENCE SCOTT & CO.).

To give the motor rotation in the reverse sense to that of the first position, the drum is moved one notch further to the right, and positions 3 and 1 engage the left- and right-hand set of contacts respectively, and thus current is supplied from the trolley to the side of the armature marked −, although the shunt which is now disconnected from the flashing resistance, is again receiving current on its + side. Another stop prevents the further rotation of drum to the right.

Fig. 562 depicts a simple series-parallel controller as applied to a 4-pole motor by Messrs. Laurence Scott & Co. for the purpose of running at two speeds. There are two sets of wipers, four of which A B C D are at one side of the controller drum, and the other three A′ B′ D′ at the other. In the "off" position none of these make contact. When the drum is turned so that these two rows of wipers make contact along the positions marked 1 and 1′ respectively, the four magnet-coils are in series, and the motor runs at half-speed. When the drum is turned so that the wipers touch along the positions 2, 2′, the magnet-coils are in parallel, and as this reduces the excitation to one-half, the armature speed will be approximately doubled.

THE DESIGN OF RESISTANCES FOR RHEOSTATS.

Resistances for use in regulating rheostats and starters must be designed with regard to the strength and probable duration of the currents to be carried. Whether made of coiled wires or of metal strips, zigzagged or strained over insulating supports, the mechanical disposition requires care that they may not when expanded by heat make short-circuits. Resistances coiled on porcelain tubes, or embedded in enamel, have been produced in many patterns. Fleming has devised special rheostats for laboratory use for absorbing power in wires strained over resilient supports. For factory use, or on vehicles, compact resistances made of grids of metallic strip, substantially insulated, and enclosed in protecting cases of perforated metal, are preferred to wire coils stretched on frames.

Size of Wires for Rheostats.—In working out the size or length of a wire which is to be used in a rheostat it must be considered how the resistance is to be used. If so arranged as to be able to radiate freely into surrounding air a smaller section is permissible than is the case if the wire is embedded in asbestos or enamel. Further, if it is for a "regulator" which may be carrying current during the whole time that the dynamo or motor is running, the wire which is to offer a given resistance must be both thicker and longer than if it is to be used in a motor "starter" which will only be in operation for a short time and then only at intervals of time separated from one another by possibly many minutes or even hours. A starter will be cheaper than a regulator of equal resistance. To facilitate the calculation of such rheostats a table is adjoined giving particulars of a number of materials used for making up such wire resistances, while a second table gives the safe currents for copper wires of different gauges. The table is given for copper (although copper is not used for such resistances), because the carrying capacity of the alloys actually used is readily ascertained simply by multiplying the carrying capacity of the copper by the coefficient given in the last column of Table XIV. It is here, of course, assumed that the conditions as to external radiating are alike. The Table is calculated on the assumption of a temperature-rise of 35 deg. Centig.: but to adapt it to any other temperature-rise it may be noticed that the permissible current will be proportional to the square-root of the temperature rise. These tables may be used, without any such alteration, in calculating regulators. But for motor starters a much higher temperature-rise may be taken, as there is plenty of time for the wires to cool down again. A third table gives the current in *iron* wires which will heat them up in one minute to about 120 deg. Centig. above the surrounding air, assuming that there is plenty of space for free radiation. Unfortunately similar tables cannot be directly calculated for all other materials.

TABLE XIV.—RESISTANCE MATERIALS FOR RHEOSTATS.

Name of Material.	Specific Resistance at 0° C.		Temperature Coefficient of Increase of Resistance per degree C.	Specific Gravity.	Coefficient to multiply into Copper Conductor of same dimensions to find resistance.	Coefficient to Multiply Safe Currents in Table XV., to obtain Safe Currents for the Various Resistance Materials.
	Microhms per centim. cube.	Microhms per inch cube.				
Constantan	50	19·7	zero or negative	8·8	30·8	0·18
German silver	20·9	8·2	0·00044	8·5	13	0·280
	30	11·8	0·00036	8·5	18·5	0·232
Iron	10	3·94	0·00450	7·8	6·2	0·40
	12	4·72		7·81	7·4	0·37
Kruppin	85	33·5	0·00077	8·8	52·6	0·14
Manganese copper	100·6	41·8	0·00004	8·7	62	0·13
Manganin	46·7	18·4	0·00033	8·94	25	0·20
Neusilber	37	15·6	0·00020	8·5	23	0·21
Nickelin	33·2	13·1	0·00030	9·0	20	0·225
	44	17·2	0·00033	9·0	27	0·190
Nickel-steel	29	11·4	0·00050	8·4	18	0·235
	75	29·5		8·5	46·5	0·150
Platinoid	32·5	12·8	0·00021	8·5	20	0·225
	51	20·1		8·7	31	0·180
Phosphor-bronze[1]	24·6	9·7	0·00039	8·6	15·2	0·255
Rheostan	47·3	18·6	0·00023	8·6	30	0·183
	100	39·4		8·6	62	0·130

N.B.—The composition of these alloys varies much as to its proportion according to the source of manufacture. For calculating the resistances of wires or strips of these materials, the simplest procedure is to calculate them as if of copper, and then multiply the resistance so found by the coefficient given in the last column of the table. As their specific gravities do not differ greatly from that of copper (8·8), they will all (except iron) weigh approximately the same as a wire of copper of same gauge and length.

---

[1] Containing 10 per cent. tin.

TABLE XV.—CURRENT-CARRYING CAPACITY OF WIRES.

The following table gives the current which can be carried by *copper wires* of different sizes. When wound in free spirals, the ultimate temperature rise will be about 35 deg. Centig. above surrounding air.

S.W.G.	Safe Current.	B. & S.G.	Safe Current.
10	55	8	55·2
11	47·3	9	46·5
12	40·3	10	38·9
13	33·4	11	32·6
14	28·2	12	27·5
15	23·2	13	23·2
16	19·4	14	19·3
17	15·9	15	16·3
18	12·6	16	13·6
19	9·6	17	11·4
20	8·2	18	9·5
22	4·7	20	6·8
24	2·4	22	4·8
		24	3·3

TABLE XVI.—IRON WIRES FOR STARTING RHEOSTATS.

Currents which will in one minute give a temperature-rise of 110 to 140 deg. Centig., if radiating freely.

S.W.G.	Current.	B. & S.G.	Current.
12	51	10	48
13	38·5	11	38·5
14	30	12	31
16	20	14	20
18	11·5	16	13
20	6·7	18	8·5
22	4·5	20	5·7
		24	2·2

THEORY OF TABLES OF WIRE-HEATING.

Let e be the emissivity, i.e. the number of calories per square inch per second for a temperature-rise of 1 deg. Centig. It is not actually a constant (being higher for black surfaces than for bright) but may be taken at an average value of 0·0025.

Let s be the specific heat (i.e. calories per gramme), and g the specific gravity (i.e. grammes per cub. cm.). Then the specific heat per unit volume, in calories per cub. cm., will be $g \times s$; or in calories per cubic inch will be $g \times s \times 16{\cdot}4$.

Then putting θ for the temperature-rise in deg. Centig., t for time in seconds reckoned from the starting of the current, ρ for the resistivity of the material, D for the diameter (in inches), and J for Joule's equivalent (42×10^6 ergs per calorie), we may write :—

$$\frac{d\theta}{dt} = \text{rate of temperature-rise}$$

$$= \frac{\text{rate of net heat-gain}}{\text{specific heat of unit-volume} \times \text{volume}}.$$

The rate of net heat-gain will be the difference between the C^2R gain and the emissivity loss. The former is $C^2J\rho \div \frac{\pi}{4} D^2$ per unit length. The latter is $e\pi D\theta$ per unit length. Hence we have

$$\frac{d\theta}{dt} = \frac{\frac{4\,C^2J\rho}{\pi D^2} - e\pi D\theta}{\frac{\pi D^2}{4} \times g \times s \times 16{\cdot}4} = \frac{16\,C^2J\rho}{16{\cdot}4 \times \pi^2 D^4 gs} - \frac{4\,e\,\theta}{16{\cdot}4 \times Dgs};$$

whence

$$\theta = \frac{4\,C^2J\rho}{\pi^2 D^3 e}\left\{1 - \epsilon^{-\frac{4et}{16{\cdot}4 \times Dgs}}\right\}.$$

When θ has attained its steady value, we have :—

$$C^2 = \frac{\pi^2 D^3 e\theta}{4\,J\rho};$$

and this is the equation used in calculating the Table XV.

But if we give θ and t values, we may then calculate a current to fulfil the equation for any prescribed diameter of wire. This has been done in calculating the Table XVI.

THE SPACING OF RESISTANCES BETWEEN THE CONTACTS.

(*i.*) *In Motor Starters*: In starting up a motor it would be best if the current could be kept at a given maximum value all the while the motor was increasing in speed. But this would require an infinite number of contacts. Therefore with a limited number of contacts, the current rises to a certain maximum when a contact is reached and falls to another specified value before the switch-arm is moved round to the next contact.

Let C_1 = maximum current allowed to flow when the switch-arm is moved on to any new contact; and C_2 = minimum value of current to be reached before switch is put on to next contact.

Let R_n = total resistance in circuit with the n^{th} contact; and
R_{n+1} = „ „ „ $(n+1)_{th}$ contact;
then if E be the back electromotive-force of the motor at the moment of switching from the one contact to the other, and V be the voltage of supply,
then

$$(V - E) \div R_n = C_2,$$

and

$$(V - E) \div R_{n+1} = C_1,$$

whence

$$\frac{R_{n+1}}{R_n} = \frac{C_2}{C_1}.$$

If C_2/C_1 is to be constant, it follows as a condition that

$$\frac{R_1}{R_2} = \frac{R_2}{R_3} = \ldots \ldots \frac{R_n}{R_{n+1}}.$$

In other words, the steps of the resistance, R_1, R_2, R_3, etc. form a geometrical series whose constant ratio is equal to C_1/C_2, and whose first and last terms are respectively V/C_1 and R_a (the resistance of the armature).

Example. Take the case of a 500 V, 30 H.P. motor which is allowed to start with current between 40 per cent. over-load and full-load value with an armature resistance of 0·4 ohm.

Then the maximum and minimum starting currents will be 63 and 45 amperes.

$$\therefore \quad R_1 \text{ will be } \frac{500}{63} = 7 \cdot 9 \text{ ohms};$$

and multiplying this by $\frac{45}{63}$, we get 5·7 for second resistance, and so on.

The resistances work out to

7·9, 5·7, 4·1, 2·95, 2·1, 1·5, 1·1, 0·78, 0·56 and 0·4,

which means that resistances in the starter will be

7·5, 5·3, 3·7, 2·55, 1·7, 1·1, 0·70, 0·38, 0·16 and FULL ON.

The following is a slide-rule method for finding these resistances, in which the number of contacts necessary must be known beforehand.

To determine the necessary number of contacts to fulfil the above stipulations.

From above we have

$$R_n = R_1 \times \left(\frac{C_2}{C_1}\right)^{n-1}$$

$$\therefore \quad \frac{R_1}{R_n} = \left(\frac{C_1}{C_2}\right)^{n-1}$$

or

$$n - 1 = \frac{\log\left(\frac{R_1}{R_n}\right)}{\log\left(\frac{C_1}{C_2}\right)}$$

or

$$= \frac{\log \frac{E}{C_1 R}}{\log\left(\frac{C_1}{C_2}\right)}.$$

Thus in the example already given

$$n - 1 = \frac{\log \frac{7 \cdot 9}{\cdot 4}}{\log \frac{63}{45}} = 8 \cdot 7, \text{ i.e. } 9.$$

Now we know R_1 and R_a are 7·9 and 0·4. We wish to place 8 geometric means between them.

Set out a distance on paper corresponding to distance between 7·9 and 0·4 on the slide-rule scale and divide it into 9 equal parts. Then, placing the divided line against the slide-rule scale between 7·9 and 0·4, the geometric means are read off opposite the division lines.

From equations given above, it will be seen how the necessary number of contacts depends upon the various stipulations.

It will be seen that the number of contacts is greater, the smaller the ratio $\frac{C_1}{C_2}$, the larger the applied E.M.F., the smaller the resistance of the motor itself and the less the maximum allowable starting current.

Another point to be noticed with these conditions of motor starting is that as the motor gets up speed the current does not decrease so fast as it did on the first contact, so that the switch must be held on the later contacts for a longer time than on the first ones.

Fig. 563 shows a graphical construction for finding the resistances to be placed between the contacts to fulfil the conditions. Current is plotted vertically and resistance horizontally; $O\,R_1$ = total resistance in at starting and $O\,C_1$ and $O\,C_2$ = maximum and minimum allowable starting currents.

Join $R_1\,C_1$ and $C_2\,a$ (= A) will give resistance to be placed between first and second notch. Draw vertical line through *a*, and where line of C_1 is cut, join to R_1 again and *a b* will give resistance to be placed between second and third notch and P *b* will be resistance which is still in on third notch.

Continue this until Q is reached where Q P = resistance of the armature.

(*ii.*) *On Dynamo Shunt Circuits to give Constant Voltage.*—An equal spacing of resistances between the contacts on dynamo regulating rheostats does not always give the best results. The proper spacing depends on the shape of the characteristic curve and the part of it at which the dynamo works. A graphical method for calculating the total resistance to regulate for any particular voltage, has already been given on p. 529, and what follows is really a continuation of this.

The problem may be stated thus. In a constant voltage dynamo, the voltage is allowed to vary two or three volts above and below the mean. Also, as the load comes on, the voltage tends to drop. It is required so to proportion the regulating resistance that whenever the voltage drops to the minimum value by moving the rheostat arm forward to the next step, the voltage will rise to the maximum permissible value and no higher.

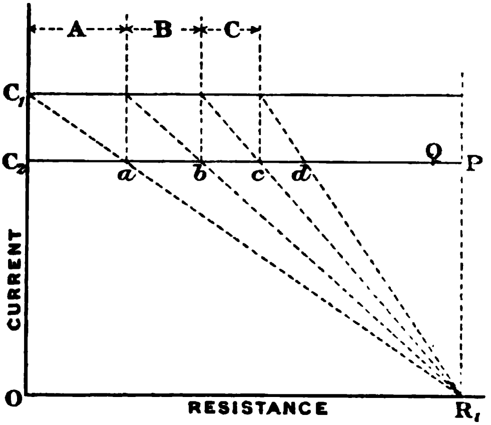


FIG. 563.

In Fig. 564, the no-load and full-load characteristics of a shunt machine have been plotted and the lines for maximum and minimum voltage have been drawn. At the points where the maximum volt line crosses, the two characteristic tangents are drawn, which meet at the point D. Two cases now present themselves: (1) that of a shunt-wound machine and (2) that of a separately excited machine. The latter is the case actually illustrated.

At the point *a*, from which the tangent was drawn, perpendicular line is drawn which cuts the line of minimum voltage in *b*. Then through *b*, is drawn O *b* *c*, cutting the maximum voltage line in *c*. From *c* perpendicular line *c d* is drawn, and so on.

The lines O*a*, O*c*, O*e*, etc., are produced to cut the line X R_0, where X R_0 = resistance in exciting circuit at no-load.

Then also the lines X R_1, X R_2, X R_3, etc., will represent the resistance in the exciting circuit at different conditions of load, and R_0, R_1, R_1, R_2, etc., will of course give the resistance between the different steps of the regulator.

In the case of a shunt excited machine, the lines *a b*, *c d*, etc., are not drawn vertical but are drawn so that when produced they will pass through the origin of the excitation curves.

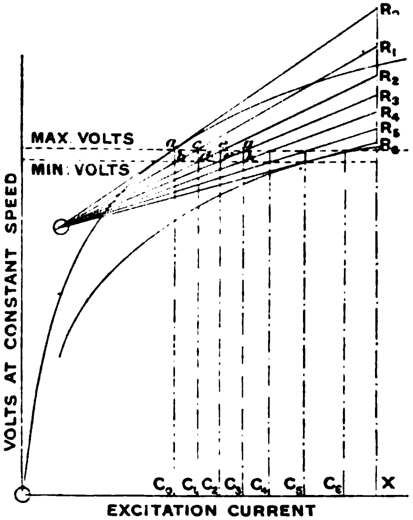


FIG. 564.

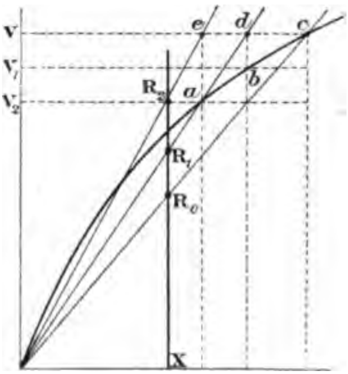


FIG. 565.

(*iii.*) *On Motor Shunt Circuits to give different Speeds.*—The regulating resistances[1] for motors to run at different speeds may also be obtained by a simple graphical construction. In Fig. 565, the no-load characteristic is shown, and the line marked supply voltage gives the excitation, when there is no regulating resistance in the shunt. The speed of motor under this state of things must also be known.

---

[1] See Gott, *Journ. Inst. Electr. Engineers*, xxxi. 1219, 1902.

Let normal speed be n, and it is required by means of steps on regulator to run at speeds n_1, n_2, n_3, etc. Then on the voltage scale is set out $\frac{Vn}{n_1}$, $\frac{Vn}{n_2}$, etc., as V_1, V_2, etc.

Project these lines across to characteristic curve and so obtain the current necessary for excitation as a b and c. Through a and b draw perpendicular lines, cutting the full voltage line in d and e, and through c d e draw lines from origin. Then when any perpendicular line is drawn in which $X R_0$ = resistance of shunt windings, then $X R_1$ and $X R_2$ give the total resistances for running the motor at speeds n_1 and n_2. Whence R_0, R_1 and $R_1 R_2$ will be the steps in the rheostat.

(*iv.*) *On Shunt Motors in series with armature, to regulate speed at full-load.*—To calculate the resistance required to be inserted in series with armature for regulation of speed at full-load. (Shunt motor will shunt direct across mains.)

Let n = no-load R.P.M. and n_1, n_2 be speed required to regulate to.

Then

$$V - CR = \frac{Vn_1}{n}$$

$$\therefore \quad R = \frac{V}{C}\left(1 - \frac{n_1}{n}\right)$$

Where

V = full applied volts.
C = full-load current.
n = no-load R.P.M.
and n_1 = required full-load R.P.M.

A Subdividing device is sometimes used on rheostats, so that resistance is cut out in smaller steps with the same number of contacts.

The accompanying Fig. 566 gives an idea of such an arrangement. Two contact-pieces are provided, one of which makes contact on two separate rings inside the ring of contacts.

Between these rings, a resistance is connected which is half the resistance between the contact buttons. As switch arm is now placed, current flows through the four resistances at the top and out. If now the switch arm is moved through half of one contact-space to the right, current flows through the first three resistances at the top, and then through the auxiliary resistance, so that moving switch arm half a contact is equivalent to cutting out half the resistance between two contacts.

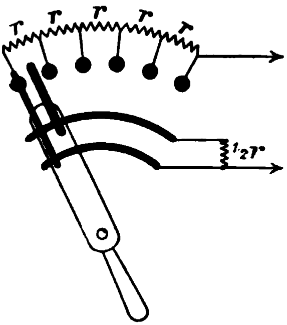


FIG 566.—SUBDIVIDING DEVICE.

The reason for the special placing of contact studs in Fig. 546 has not yet been explained.

When the switch arm is moved round clockwise from M and N, contact is made on *a* and *f* at the same moment. Now the contact *f* is longer than *a*, it reaching in fact to a point corresponding to the centre of *b*, so that when switch arm is moved round further it makes contact on *b* before it leaves *f* and then on *g* before it leaves *b* and so on, thus cutting out resistance in 8 steps where before it was cut out in 4.

Liquid Resistances.—Liquid resistances consisting of iron plates immersed in water, or in salt or soda solutions, have for many years been used as regulating rheostats and starters, but more often to provide artificial non-inductive loads when testing dynamos and alternators. They are simpler in construction than ordinary rheostats, and also have the advantage that they do not heat up so fast, owing to the high specific heat of water.[1]

The resistance may be regulated in two ways, viz. either by moving the plates nearer together or farther apart from one another, or by immersing a smaller or larger area of plate.

---

[1] In connection with this, it has been suggested that the wire resistances of ordinary starting rheostats might be immersed in water, so that the heat generated in them may be dissipated more easily, thus enabling a smaller section wire to be used, and therefore also, a shorter length of it.

Small rheostats, in which the first method is adopted, may be made of U-tubes, with the electrodes moving up and down the tubes. In motor starters the method usually adopted is to have a wedge-shaped blade which is gradually introduced into the water and which finally makes contact with the other electrode for full "on" position. Resistances can be made up for different purposes, by using different amounts of solvent.

The chief troubles with liquid resistances are the evaporating of the water and the creeping of the dissolved salt or of the liquid. The temperature of the water cannot of course be raised above boiling-point; and so, in rheostats used for testing large generators, arrangements are made for a constant flow of water through the rheostat, the flow being so regulated that the overflow is as near boiling-point as possible. Smaller rheostats must be frequently inspected and filled up with water when necessary. To obviate creeping, vaseline may be smeared round the bath just above the liquid line. For motors up to 10 H.P. a very compact liquid resistance has lately been introduced by Woolliscroft. It is provided with no-volt and overload release.

An article in the *American Electrician*, xv. 512, Oct. 1903, deals with liquid and submerged rheostats.

CHAPTER XXVII.

TESTING DYNAMOS AND MOTORS.

TESTS to be applied to dynamos are of two kinds, viz. those which relate to the resistance and insulation of the various parts, and those which relate to the efficiency under various loads.

Testing Construction.—The resistance of the various parts of the armature coils, of the field-magnet coils, and of the various connexions, may be tested in the ordinary manner, by means of a Wheatstone's bridge. The only point of difficulty lies in measuring such small resistances as those of armatures and of series coils, which are often very small fractions of an ohm. In this case the best method is to employ a modern potentiometer, such as that of Crompton. Failing this, the following is useful. By means of a few accumulator cells send a strong current through the coil or armature whose resistance is to be measured, interposing in the circuit an amperemeter. While this current is passing, measure, by means of a sensitive voltmeter, the fall of potential between the two ends of the coil. By Ohm's law, the number of volts of fall of potential divided by the number of amperes will give the resistance in ohms. Additional accuracy may be secured by connecting in the circuit a strip of stout German silver, as recommended by Lord Rayleigh, of known resistance, and comparing the fall of potential between the two ends of the strip with the fall of potential in the coil. The ratio of the two falls of potential will equal the ratio of the resistances.

The internal resistance of a dynamo when warm after working for a few hours is considerably higher than when it is cold. Tests of resistance ought therefore to be made both before and after the dynamo has been running.

Testing Insulation-Resistance.—The rational mode of testing the insulation in the workshop is to apply a high voltage—say from 2000 to 4000 volts—and see whether the insulation resists being pierced. The electric tension or stress to which the dielectric is subjected, tending to pierce it, varies as the square of the volts. The most convenient way of applying the tests is to use a small alternate-current transformer, giving the requisite voltage. All dynamos, motors and transformers intended for high voltage work should be tested at double the volts at which they are intended to work. Tests of the insulation-resistance between the coils of a dynamo and its metal cores or frame by use of a Wheatstone's bridge, made regularly day by day, are useful as far as they serve as a guide to the way in which the machine is being cared for; since damp and dirt lower the insulation, and if neglected promote likelihood of a break-down. Evershed's ohmmeter is an instrument appropriate for these tests.

Testing Temperature-Rise.—The instructions given by the Admiralty for tests of temperature are that at the end of a six hours' run at full-load, no accessible part of the armature or field-magnet shall show a temperature of more than 70° Fahr. above that of the dynamo room. It is usual to employ thermometers with narrow cylindrical bulbs which can be inserted in the armature, or laid upon it and covered with a pad of cotton-wool while the test is made.

Testing Performance and Efficiency.—The testing of the efficiency and working capacity of a dynamo, whether working as generator or as motor, is a more serious matter, and involves both electrical and mechanical measurements.

In the case of the dynamo generating currents, measurements must be made (*a*) of the mechanical input and (*b*) of the electrical output.

In the case of the motor doing work, measurements must be made (*a*) of the electrical input, and (*b*) of the mechanical output.

Measurement of Power.—The general methods of measuring the power mechanically are as follows:—

(*a*) *Indicator Method.*—By taking indicator diagrams from the steam-engine which supplies the power.

(*b*) *Brake Method.*—By absorbing the power delivered by the machine, at a friction brake such as that of Prony, Poncelet, Appold, Raffard, or Froude.

(*c*) *Dynamometer Method.*—By measuring in a transmission dynamometer or ergometer, such as that of Morin, von Hefner-Alteneck, Ayrton and Perry, or of F. Jervis-Smith, the actual mechanical power of the shaft or belt.

(*d*) *Balance Method.*—By balancing the dynamo or motor on its own pivots and making it into its own ergometer.

(*e*) *Electrical Method.*—By making the motor drive the dynamo which supplies it, measuring electrically the work given out in the one, or absorbed by the other, and then measuring, either mechanically or electrically, the difference.

(*f*) *Steam Consumption.*—In cases where indicators cannot be used (as for example in tests of steam turbines), the weight of steam consumed per hour, as measured by feed-water supplied to the boiler or by the water from the condenser, may be taken as a measure of the gross power.

(*a*) *Indicator Method.*—The operation of taking an indicator diagram of the work of a steam-engine is too well known to engineers to need more than a passing reference. It measures the gross power imparted thermally to the engine, not the nett power given by the engine to the dynamo. This method is, however, not always applicable, for in many cases the steam-engine has to drive other machinery, and heavy shafting for other machinery. In such cases the only remedy is to take two sets of indicator diagrams, one when the dynamo is at work, the other when the dynamo is thrown out of gear, the difference being assumed to represent the horse-power absorbed by the dynamo.

(*b*) *Brake Method.*—The friction-brake of Prony is well known to engineers, but the same can hardly be said of the more recent forms of friction dynamometers. Various improvements have been introduced in detail from time to time by Poncelet, Appold, and Deprez. In Prony's method the work is measured by clamping a pair of wooden jaws round a pulley on the shaft; the torque on the jaws being measured directly by hanging weights on a projecting arm with a sufficient moment to prevent rotation. If p is the weight which at a distance l from the centre balances the tendency to turn, then the friction force f multiplied by the radius r of the pulley will equal p multiplied by l.

This may be written,

$$\text{Torque} = fr = pl.$$

From which it follows that

$$f = \frac{pl}{r}.$$

If n be the number of revolutions *per second*, then $2\pi n$ is the number of radians per second, or in other words, the angular velocity, for which we use the symbol ω, and $2\pi nr$ is the linear velocity v at the circumference. Now the work per second, or power, is the product of the force at the circumference into the velocity at the circumference, or

$$w = fv = \frac{pl}{r} \cdot 2\pi nr = 2\pi npl.$$

If p is measured in pounds' weight, and l in feet, then, remembering that 550 foot-pounds per second go to one horse-power, we have,

$$\text{horse-power absorbed} = \frac{2\pi npl}{550};$$

or, if p is expressed in grammes' weight, and l in centimetres, it must be divided by $7 \cdot 6 \times 10^6$ to bring it to horse-power.

The latter improvements imported into the Prony brake are of great importance. Poncelet added a rigid rod at right angles to the lever, and attached the weights at the lower end. Appold substituted for the wooden jaws a steel strap, giving a more equable friction, and therefore having less tendency to vibration. Raffard[1] substituted a belt differing in breadth, and therefore offering a variable coefficient of friction, according to the amount wrapped round the pulley.

---

[1] For further accounts of these instruments the reader is referred to Weisbach's *Mechanics of Engineering*; Spons' *Dictionary of Engineering*, Article "Dynamometer"; Smith's *Work-measuring Machines*; a series of articles in the *Electrician*, 1883-4, by Mr. Gisbert Kapp; *Proc. Inst. Mech. Eng.* 1877, p. 237 (Mr. Froude); *Rep. Brit. Assoc.*, 1883 (Prof. Unwin); *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 346 (Profs. Ayrton and Perry). See also *Official Report* of the Electrotechnical Exhibition of Frankfort, 1891, for the brake tests made on the turbines at Lauffen. The article in the *Encyclopædia Britannica Supplement* (1902) by Prof. Dalby, gives an admirable account of all important forms.

Further modifications of this kind of brake dynamometer have been made by Professor James Thomson, Professor Unwin, M. Carpentier, and by Professors Ayrton and Perry. The friction of a turbine wheel was also applied as a dynamometer brake by the late W. Froude. Professor Alex. B. W. Kennedy has obtained excellent results from the use of a rope brake.

As all these brake dynamometers measure the work by destroying it, it will be seen that though they are admirably adapted to measure the work furnished by a motor, they cannot, except indirectly, be applied to measure the work supplied to a dynamo. Some experience in working with these machines is essential if reliable results are to be obtained; but with the more modern forms of instruments, such as those of Poncelet and Raffard, the results are very good. The great secret of success is to keep the friction surfaces well lubricated with an abundant supply of soap and water.

Probably the most accurate method of measuring power by absorbing it is to use as brake a dynamo of high and known efficiency on a load of lamps, the output being measured by amperemeter and voltmeter.

(*c*) *Dynamometer Method.*—The Prony brake was styled above a brake dynamometer; but the true dynamometer for measuring transmitted power does not destroy the power which it measures. Transmission dynamometers may be divided into two closely allied categories: those which measure the power transmitted along a belt, and those which measure power transmitted by a shaft.

In the case of transmitting power by a belt, the actual force which drives is the difference between the pull in the two parts of the belt. If F' is the pull in the slack part of the belt before reaching the driven pulley, and F the pull in the tight part of the belt after leaving the driven pulley, then $F - F'$ represents the nett pull at the circumference, and $(F - F') \times r$ is the torque T. Then if n is the number of revolutions *per second* the angular velocity ω will be equal to $2\pi n$. This gives us as the work per second, or power,

$$w = \omega T = fv = 2\pi n r (F - F').$$

As before, if F is expressed in pounds' weight and r in feet, the expression must be divided by 550 to bring to horse-power; or must be divided by $7 \cdot 6 \times 10^6$ if the quantities are expressed in grammes' weight and centimetres.

A dynamometer which can be applied to a driving belt, and actually measures the difference $F - F'$ in the tight and slack parts of the belt, has been designed by von Hefner Alteneck, and is commonly known as Siemens' belt dynamometer.[1] Other forms have been devised by Sir F. J. Bramwell, W. P. Tatham,[2] W. Froude, T. A. Edison and others. Nearly all of these instruments introduce additional pulleys into the transmitting system, causing additional friction.

Much more satisfactory are those transmission dynamometers which measure the power transmitted by a shaft. In nearly all instruments of this class there is a fixed pulley keyed to the shaft, and beside it a loose pulley connected with it by some kind of spring arrangement, so set that the elongation or bending of the spring measures the angular advance of the one pulley relatively to the other; this angular advance is proportional to the transmitted torque. To this class of instrument belongs the well-known dynamometer of Morin, in which the displacement of the loose pulley is resisted by a straight bar spring, the centre of which is attached to the driving shaft. Modifications of the Morin instrument have been devised by Easton and Anderson, Heinrichs,[3] Ayrton and Perry,[4] Murray,[5] W. E. Dalby, and the Rev. F. Jervis-Smith, of the Millard Engineering Laboratory, Oxford. Of the last-named instrument, a full description and cut were given in former editions of this book.

(*d*) *Balance Method.*—With small motors there arises the difficulty that the ordinary means of measuring the work they perform introduce relatively large amounts of extraneous friction. The motor to be tested is placed with its armature spindle between centres, or on friction wheels, and the weight of the field-magnets and frame is very carefully balanced with counterpoise weights. In Fig. 567, B D represents the field-magnets and frame of the motor duly counterpoised, and E is the armature. When the current is turned on, the armature tends to rotate in one direction and the field-magnets in the other; the angular reaction being, of course, equal to the angular action. If the reaction which tends to drive the field-magnets round be balanced by applying a force P (for example that of a spring balance) at the point C of the frame A B C D, then the moment of this force P d, measures the torque, exactly as in the Prony brake. Hence it will be seen that the motor has become its own dynamometer, the magnetic friction between the armature and the field magnet being substituted for the mechanical friction between the pulley and the jaws. A modification of the balance method due to Herman Müller, consists in swinging the dynamo in a cradle pendulum fashion, from the driving-shaft, and estimating the power absorbed by the displacement from the vertical line.

---

[1] One form of the Siemens dynamometer is described by Hopkinson, *Proc. Inst. Mechan. Eng.*, 1879. A more modern form is described by Schroter, *Bayerisches Industrie- und Gewerbeblatt*, 1883.

[2] *Journ. Franklin Institute*, Nov. 1886.

[3] See *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884.

[4] *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 163, 1883.

[5] *Ibid.*, xviii. 1889.

M. Marcel Deprez and Professor C. F. Brackett have proposed to apply the balance method to dynamos in action. Professor Brackett places the dynamo in a sort of cradle, balanced on centres that lie in the axis of rotation, and measures the torque between the armature and field magnets, and multiplying this by the angular velocity $2\pi n$, obtains the value of the power transmitted to the armature.

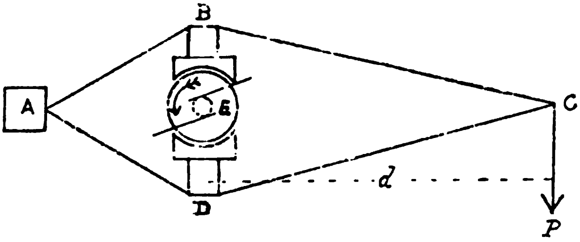


FIG. 567.—REV. F. J. SMITH'S METHOD OF TESTING MOTORS.

All these several dynamometric methods necessitate the use of a speed-indicator to count the number of revolutions n, which enters as a factor into the calculation of horse-power. The number of revolutions *per second* n being known, the angular velocity $\omega = 2\pi n$ can be calculated. This only requires to be multiplied by the torque $T = Fr$ to give the power or work-per-second w. And if T is expressed in pound-feet, then,

$$\text{Horse-power} = \frac{2\pi n F r}{550} = \frac{\omega T}{550}.$$

(*e*) *Electrical Methods.*—There are several varieties of this modern method of testing, and they involve the use of two or in some cases three machines. Two machines, one to act as generator, the other as motor, are connected together both electrically and mechanically, so that the power is *circulated* between the two machines, passing from generator to motor electrically, and returned from motor to generator mechanically. The power given out by the generator machine, and that absorbed by the motor, are measured electrically. In the original plan of Dr. J. and E. Hopkinson,[1] the small additional power required to drive the generator was supplied by a steam-engine and measured mechanically by a dynamometer. By thus circulating the power it is possible to test a pair of machines at say 500 horse-power each, using only a 50 horse-power steam-engine. Modifications of this method for the purpose of obviating all mechanical measurements have been suggested by Lord Rayleigh,[2] Major Cardew,[3] whose method dates from 1882, M. Menges,[4] Mr. Ravenshaw[5] and Mr. Swinburne.[6]

All these methods are far more accurate than the rough mechanical methods of earlier date, and each has its advantages, but Hopkinson's method requires two similar machines, and Cardew's requires three machines, one of which must be powerful enough to run the other two. In Swinburne's method the loss of power due to resistance of conductors is calculated, and this deducted from the whole loss of power in the machine gives the "stray power" made up of losses due to eddy-currents, friction and magnetic hysteresis, which are thus measured together. This stray power is determined by using the machine as a motor, the field-magnets being separately excited so that the armature has the same magnetic induction as at full-load, the electromotive-force applied to it being such as to drive it at its normal speed. Only a small generating dynamo is required to furnish the current for this. When matters are so arranged that the machine to be tested runs at its normal speed, the power used in driving the machines (which is measured electrically by taking readings of the volts on the armature and the amperes flowing through it and multiplying up) is equal to the stray power at full-load.

---

[1] *Phil. Trans.*, 1886, ii. 347. See also *Electrician*, xvi. 347, 1886; and *Electrical Review*, xviii. 207 and 230, 1886.

[2] *Electrical Review*, xviii. 242, 1886.

[3] *Ibid.*, xix. 464, 1886; and *Electrician*, xvii. 410, 1886; and xxi. 275, 1887.

[4] *Electrician*, xvi. 371, 1886.

[5] *Electrical Review*, xix. 424 and 437, 1886.

[6] *Ibid.*, xxi. 181 and 215, 1887.

An example may be useful. Suppose we have to test a large 50 kilowatt shunt-wound dynamo, giving 500 amperes at 100 volts at 720 revolutions per minute, and that $r_a = 0{\cdot}006$ ohm, and $r_s = 12$ ohms, the lost amperes will be $100 \div 12 = 8{\cdot}5$, total current say 508 amperes; hence lost volts $508 \times 0{\cdot}006 = 3$ volts; whence E = 103 volts. Watts lost in armature $= 508 \times 508 \times 0{\cdot}006 = 1548$. Watts lost in shunt coil $= 100 \times 100 \div 12 = 833$. Now arrange any small dynamo, of say 2 H.P., to give out current at 103 volts; and from this run the large dynamo that is to be tested, as a motor, with no other load than its own friction, hysteresis and eddy-currents. It will run under 720 revolutions, since with such small current its armature produces no demagnetizing action to quicken it up. Therefore add some resistance to its shunt till it comes up to speed. Then measure the current it is taking; this multiplied by E gives the stray power. Suppose it takes 9 amperes, then the stray power is $103 \times 9 = 927$ watts. We may at once reckon out the efficiencies. The losses now known are $1548 + 833 + 927 = 3308$. Add this to the 50,000 watts of nett output, and we get the gross output 53,308. Hence we have the following:—

$$\text{Gross efficiency} = \frac{52381}{53308} = 98{\cdot}3 \text{ per cent.}$$

$$\text{Electrical efficiency} = \frac{50000}{52381} = 95{\cdot}5 \quad ,,$$

$$\text{Nett efficiency} = \frac{50000}{53308} = 93{\cdot}8 \quad ,,$$

Mr. Kapp[1] has devised a method of testing which permits the commercial or nett efficiency to be determined electrically with far higher accuracy than is possible with any mechanical dynamometer. It requires two machines of nearly equal power, one G to run as generator, the other M as motor, together with a small auxiliary machine X of normal voltage, to which the other two are coupled in parallel, Fig. 568. The armatures of G and M must also be coupled together mechanically, and the field of M must be weakened by use of a rheostat, so that it may run as a motor. X gives the current necessary for exciting and for making up the difference between the currents in G and M. Insert an amperemeter from one brush of G to one of M to measure the currents. Take a reading of the G current when the auxiliary current is led in on the right, and another reading of the M current when the auxiliary current is led to the left. As the volts are the same in each case, the ratio of the two currents is the efficiency of the combination of the two machines; and the square root of the ratio of the two readings is the efficiency of either machine.

---

[1] See *Electrical Engineer*, Jan. 22, 1892, and *Electrician*, July 5, 1895, 319.

Testing Separate Losses.—In the preceding paragraph no distinction was made between the three sources of loss which go to make up the stray power, namely, friction, eddy-currents and hysteresis. It was indeed possible to separate the eddy-current loss from the others by making experiments at different speeds,[1] because the eddy-current loss increases proportionately to the square of the speed, whilst the other losses are approximately proportional simply to the speed. The power thus wasted was given to the armature by a motor and measured electrically. In 1891, a method of separating these losses was independently published by Kapp[2] and by Housman.[3] From the latter's paper is taken Fig. 569, which shows the method adopted by both these engineers. The method is as follows:—Let the field-magnet be separately excited to a constant value. Then measure the currents required to run the armature as a motor with no-load at different speeds, by using different volts. The results when plotted out as a curve give a straight line A B, Fig. 569, cutting the axis of current above the origin. A horizontal line A D, through A, divides the ordinates, such as C B, into two parts; one C D, which represents the losses that are proportional to speed; and another D B which represents those that

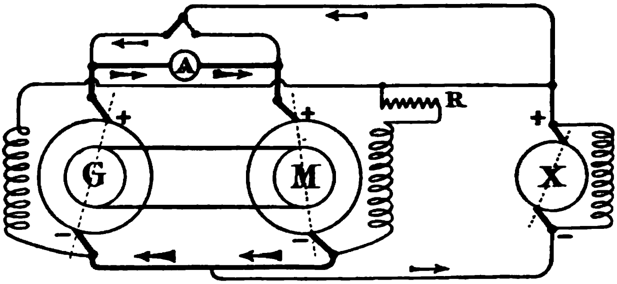


FIG. 568.—KAPP'S METHOD OF TESTING EFFICIENCY.

---

[1] *Journ. Inst. Electrical Engineers*, xviii. 620, 1889.

[2] *Electrician*, xxvi. 699, 1891.

[3] *Ibid.*, xxvi. 700, 1891; also *Journ. Inst. Electrical Engineers*, xx. 298, 1891.

are proportional to the square of the speed. To separate friction of bearings and brushes, the armature should be coupled direct to another similar machine, the latter running without excitation of magnets, when the increase of current needed to drive will give a measure of frictional loss, and from this the lines E F and G H may be plotted out. Or the unexcited machine may be coupled to a small motor to drive it, and the power required to drive it when the only load is that of the frictional loss may be measured electrically on the motor. If a second set of observations are made with a field of different strength, a second line A′ B′ will be obtained, which will be above or below A B, according to whether the change of field has increased or diminished the total losses. The minimum total loss usually occurs with an excitation that makes the flux-density B in the armature about 95,000 or 105,000; for when the excitation is pushed further, not only does hysteresis become much greater, but the eddy-currents in shaft and pulley due to the leakage of magnetic lines are greater. If the line A B curves upwards at the higher values, it shows that the eddy-currents in the armature are producing perceptible demagnetization.

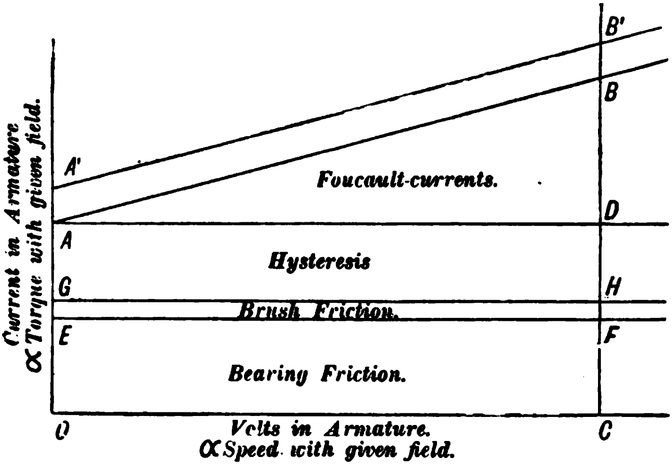


FIG. 569.—SEPARATION OF LOSSES IN DYNAMO.

Additional Losses at Full-Load.—Reference was made on pages 219 and 523 to a certain increase in the losses at full-load, attributable in part to eddy-currents in the copper, to eddy-currents in the pole-pieces, and to the unequal distribution of current between the armature circuits. Dettmar[1] has pointed out that there is also an increase in the iron-losses arising as a secondary consequence of the magnetic distortion. If by reason of distortion the flux is increased in one part of the iron and diminished in another, inasmuch as some of the losses are proportional to B^2 and others to $B^{1 \cdot 6}$, the total iron-loss will be greater than that calculated from the *mean* value. If mean values are taken, then the exponent for eddy-current losses may rise from 2 to 2·1 in the teeth, or 2·2 in the pole-pieces; while that for the hysteresis losses rise from 1·6 to 1·76 in the teeth, or to 2 in the pole-pieces. He carried out a careful series of experimental measurements in support of his views.

Testing of Combined Plant.—It is usual to specify for combined plant that the efficiency of the combined engine and dynamo taken together, on a run of several hours at full-load, shall reach some prescribed figure; and that the steam consumption per kilowatt-hour of output shall also not exceed a given limit. The requirements of British consulting engineers have been for many years exacting, with the result that manufacturers and contractors[2] have attained to exceedingly high efficiencies.

As an example of tests of a continuous-current combined plant we may take those made by Professor A. B. W. Kennedy in May 1893, at Thames Ditton, of a 123 kilowatt shunt-wound dynamo by Holmes & Co., direct driven from a two-crank compound Willans engine (condensing) at 335 revolutions per minute. During a six hours' run with a load of 1010 amperes at 120 volts (or 121·5 kilowatts, or 162·8 horse-power electrical output), steam was being used at 3314 lbs. per hour, or 27·3 lbs. per kilowatt hour, or 20·3 lbs. per horse-power hour, of the nett electrical output. The internal horse-power during same time as measured with indicators, was 190·2, giving an efficiency of 85·6 per cent. The steam used per horse-power indicated was 17·4 lbs. The rise of temperature at the end of the run was found to be 40° C. above that of the surrounding air. Tests were made also at ¼, ½ and ¾ load, also when the dynamo was run on open circuit, excited and unexcited, and when the engine was run alone uncoupled. The results are plotted out in the accompanying diagram,

---

[1] *Elektrotechnische Zeitschrift*, xix. April 1898; and xx. 203, 1899.

[2] See a remarkable paper by Mr. R. E. Crompton, *Proc. Inst. Civil Engineers*, cvi. 1891.

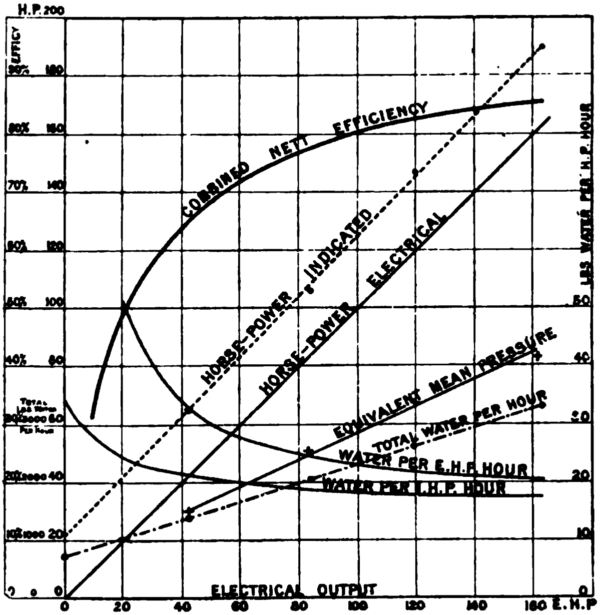


Fig. 570.—Test of Holmes-Willans Combined Plant (Kennedy).

Fig. 570. When worked out in detail it appears from these tests that the efficiency of the engine by itself is 89·5 per cent.; that of the dynamo by itself 95·6 per cent.

The tests of Parsons' steam turbine, made by Ewing in 1892, showed a steam consumption of 27 to 28 lbs. per kilowatt-hour at full-load, and of 30 to 32 lbs. per kilowatt-hour at half-load; 15½ lbs. per kilowatt-hour are now claimed for the recent steam turbines of 3500 kw. size.

An elaborate arrangement of speed-cones for dynamo-testing, designed by Prof. Ayrton, is described in *Industries*, June 22, 1888. For detailed accounts of tests on dynamos the reader is referred to the following sources: *Report of Committee of Franklin Institution*, 1878; *Official Report of Munich Electric Exhibition*, 1882; also Prof. W. G. Adams' Inaugural Address, *Journal of Society of Telegraph Engineers and Electricians*, xiv. 4, 1885; also Reports of Electrical Exhibition at Philadelphia, 1884, published in *Journal of the Franklin Institution*, 1885; tests of arc-lighting dynamos at Melbourne Exhibition, by K. L. Murray, *Journal Institution Electrical Engineers*, xviii. 1889; tests of dynamos (Desroziers, Edison, Gramme, etc.) at Paris Exhibition of 1889, by A. Minet, *La Lumière Électrique*, xxxv. 1889; tests on Stanley Arc Alternator by Duncan and Hassen, *Electrician*, xxvi. Jan. 1891; tests of a Goolden dynamo and Willans engine, separating the losses, *ib.* xxvi. p. 36, 1890; tests of a Wenström dynamo, separating the losses, by Duncan, *Electrical Review*, xxvi. 116, Jan. 1890; papers on Causes of Losses, by Hummel, in *Elektrotechnische Zeitschrift*, viii. 1887, and xii. 1891. At the Frankfort Exhibition of 1891, very careful tests were made of numerous machines under very favourable conditions. These are detailed in the second volume of the *Official Report*, published at Frankfort in 1893. The paper on the Testing of Tramway Motors, by M. B. Field, in *Journal Institution Electrical Engineers*, xxi. 1902, discusses various methods of testing, and gives results in detail. Friction losses in dynamos have been discussed by Kinzbrunner, Van Rossem and by Dettmar in the *Elektrotechnische Zeitschrift*, vol. xxiv. for 1903; also by Dettmar in vol. xx. p. 380, 1899.

MANAGEMENT OF DYNAMOS.

On Coupling Two or More Dynamos in One Circuit.—It is sometimes needful to couple two or more dynamos together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. Thus it may occur that two dynamos, neither of which can safely carry a greater current than 1000 amperes, are required to supply jointly a 2000-ampere current; or two machines, each of which can run at 60 volts, are required to furnish an electromotive-force of 120 volts. Simple as these cases may seem, it is not so easy to carry them out, because it depends upon the construction of the machine, and especially upon the mode of excitation of the field-magnets, whether they can be coupled together without interfering with each other's running. For it may, and does, occur that if not rightly arranged, one machine will absorb energy from the other and be driven as a motor instead of adding anything to the energy of the circuit.

Coupling Continuous-current Machines in Series. — Series-wound dynamos may be united in series with one another for the purpose of doubling the electromotive-force. Thus two Brush machines, each working at 10 amperes, and each capable of working 6 arc-lamps, may be joined in one circuit with 12 arc-lamps in series. The only needful precaution is to see that the + terminal of one machine is joined to the – terminal of the other, precisely as with cells of a battery. Shunt-wound dynamos may also be coupled in series, though the arrangement is not good unless the two shunt-coils are also put in series with one another, so as to form one long shunt across the circuit. Compound-wound dynamos may be connected in series with one another, provided the shunt parts of the two are connected as a single shunt, which may extend simply across the two armatures (double short-shunt), or may be a shunt to the external circuit (double long-shunt), or may be a mixture of long and short shunt. The same considerations apply to more than two machines. The coupling of alternate-current dynamos introduces considerations of a special kind, which are dealt with in Vol. II.

Coupling Dynamos in Parallel.—Dynamos, to run well in parallel without any special coupling devices, should have a falling characteristic (see p. 330), for if the characteristic rises, then the machine yielding the greatest share of the current will have its electromotive-force increased thereby and will yield more and more current until it takes all the load and drives the other machines as motors. If, on the other hand, the electromotive-force falls with an increase of current the load is automatically divided between the machines. It is, of course, possible for a machine to have a rising characteristic when run at a perfectly constant speed, and yet through the slowing of the engines with increased load the characteristic of the combined plant may be a falling one. In such a case where each dynamo is driven by a separate engine parallel working would be possible.[1]

Simple shunt machines always have a falling characteristic and therefore there is no great difficulty in running them in parallel, as indeed is done on a large scale every day in central lighting stations. The chief precaution to be taken is that, whenever an additional dynamo has to be switched into circuit, its field must be excited, and it must be run at full speed before its armature is switched into connexion with the mains, otherwise the current from the mains will flow back through it and overpower the driving force.[2]

---

[1] Sayers, *Journ. Inst. Elec. Engs.*, xxiv. 137, 1895.

[2] See Burstyn, in the *Zeitschrift für angewandte Elektricitätslehre*, 1881, p. 339, also Schellen (2nd edition), p. 717; Ledeboer, in *La Lumière Électrique*, xxvi. 210, 1887; Meylan, in *La Lumière Électrique*, xxvi. 379, 1887; and

Two series dynamos cannot be coupled in parallel in a circuit without a slight rearrangement, otherwise they interfere. For, suppose one of them to fall a little in speed, so that the electromotive-force of one machine is higher than that of the other machine with which it is in parallel, the machine having the higher electromotive-force will then drive a current in the wrong direction through the other machine, reversing the polarity of its field-magnets and driving it as a motor. To obviate this, Gramme made the suggestion that the machines should be coupled in parallel at the brushes as well as at the terminals. This is shown in Fig. 571. The terminals T_1 T_1 of one machine are respectively joined to T_2 T_2 of the second machine, and a third wire joins B_1 with B_2. Triple-pole switches are convenient. If both machines are doing precisely equal work, there will be no current through the wire B_1 B_2. If either machine falls behind, part of the current from the other machine will flow through B_1 B_2 and help to maintain the excitement of the magnets of the weaker machine. This effectually prevents reversals. Another method of coupling two series machines is to cause each to excite the other's field-magnetism. This equalizes the work between the two machines.

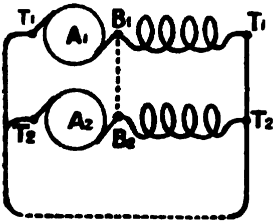


FIG. 571.—COUPLING OF TWO SERIES DYNAMOS IN PARALLEL.

Coupling of Compound Dynamos in Parallel.—In working compound dynamo machines in parallel circuit, some difficulty has been found, on account of their tendency to behave in the same manner as series-wound machines. Mr. Mordey first pointed out that the difficulty might be overcome by connecting the parallel machines in such a way that not only are the shunt portions of the field-magnets in parallel circuit, but the series circuits of the field-magnets are also a shunt on one another; in other words, by connecting the brushes as well as the terminals, in parallel circuit, precisely as Gramme had done for series-wound machines.

In Fig. 572, A_1 A_2 are the armatures of two compound dynamos, T_1 T_1 and T_2 T_2 are the terminals; the wire B_1 B_2 acting in conjunction with the lead T_1 T_2 on the left, puts the armatures in parallel. The dynamos should each be furnished with a switch s in

---

Feussner, in *Zeitschrift für Elektrotechnik*, 1887, 108; also Prof. Puffer in *Technology Quarterly*, v. 380, 1893. See also the special mode devised by S. S. Wheeler, U.S. Patent No. 335,048 of 1886.

the shunt circuit; they should each also have a switch *m* in their main circuit between the armature part and the point where the shunt circuit joins on, so that the armature part may be interrupted without interrupting the shunt circuit. The connecting wire from brush to brush, which should be at least as thick as the mains, should also be furnished with a switch *z*. Suppose dynamo No. 1 is at work alone, its two switches s_1 m_1, will be closed. If, now, dynamo No. 2 is to be thrown in, the following order must be observed. First get up the speed of No. 2 to its full value, then close s_2, then *z*; this will fully excite its magnetism; lastly, close m_2. When No. 2 has to be thrown out of circuit the order must be exactly reversed: first open m_2; then *z*; then s_2; lastly, slow down the machine. A special combination-switch, which will perform these successive operations in their proper order, is desirable.

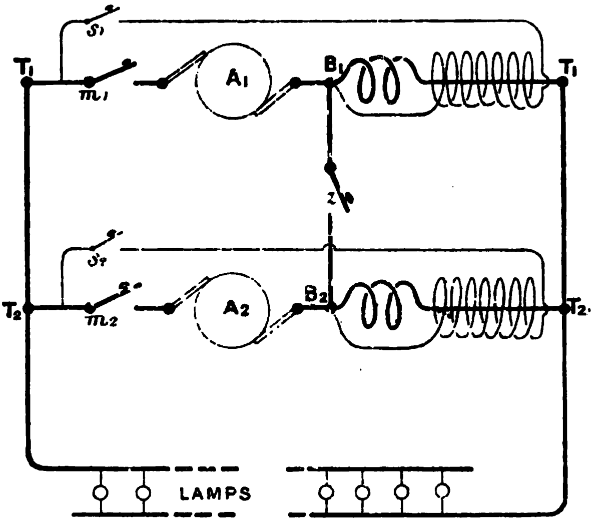


FIG. 572.—COUPLING OF TWO COMPOUND DYNAMOS IN PARALLEL.

When compound dynamos are connected in this way,[1] they work quite satisfactorily, and exercise a considerable power of mutual adjustment; for any increase in the current from one machine is divided equally among the series coils and does not raise the electromotive-force of one machine more than another.

---

[1] The method proposed by M. Ledeboer in *La Lumière Électrique*, xxvi. 210, 1887, is practically identical with the above.

Not only does this control exist with similar compound dynamos, but it may be relied on when the dynamos are unlike in size, power and speed. For instance, large and powerful machines may be worked in parallel circuit with smaller machines of various powers and each will do its proper share of the work. The resistance of the series coil of each machine must, in this case, be adjusted so that the division of the current among the coils is in proportion to the powers of the machines. If the switch *z* is permanently kept closed the effect is to make the excitation of the field of all the machines depend upon the total output of the station, and thus it is possible to compensate for a drop in volts which takes place in the mains.

GENERAL INSTRUCTIONS IN USE OF DYNAMOS.

Position of Dynamo.—The place chosen should be dry, free from dust and preferably where a cool current of air can be had. If the dynamo is not direct-driven, sufficient room should be allowed for a belt of proper length.

Foundations.—It is most important to secure good foundations for every dynamo; and if the dynamo is direct-driven, but is not on the same bed-plate as the engine, a foundation large enough for both together should be laid down. Stone or concrete may be used, or brick built with cement, having a large thick stone bedded at the top. For small dynamos the holding down bolts may be set with lead or sulphur in holes in the stone top; but for large dynamos the bolts should be long enough to pass right down to the bottom, where they should be secured into iron plates built in. If long holes are left in the foundations for the holding-down bolts, they should be filled in with thin cement after the latter have been put in place.

Sliding Rails.—All belt-driven dynamos ought to be provided with tightening gear to take up the slack. If the dynamo is not provided with sliding rails under its bed-plate, and tightening screws, the less desirable method of employing a tenting pulley may be used. In any case the bed for the dynamo must be quite level, and its shaft set properly parallel with the driving pulley.

Setting Up.—Before setting up any dynamo or motor which has been long unused, or has been exposed to changes of climate, it should be kept for a few days in a warm and dry place. For the insulation materials are liable to absorb damp that can only be slowly dried out. Nothing is more likely to cause a break-down than to attempt to run a machine that is not thoroughly dry.

Before Starting.—Examine the dynamo before it is set running for the first time. Remove caps of bearings and clean them and the journals. Replace them, but do not screw up too tightly. See that lubricators are filled, and the drip properly adjusted. Where the bearings are self-oiling see that the oiling ring works properly. Use *copper* oil-cans. Turn the armature round by hand to see that nothing catches and no loose wires or waste are adhering to it. Test the centring of the armature by measuring with a small wooden wedge the width of the clearance all round. Clean up the commutator with the finest glass-paper (emery paper must not be used), and note carefully that no dirt or copper-dust is lodged between the bars of the commutator. A stiff dry hog-brush will be useful here. See that the brush-holders work rightly, and that the hold-off catches, if any, are in order. See that each brush is properly trimmed (i.e. filed off at the proper bevel at the ends. Some makers provide a special tool to guide the file at the proper angle). Adjust the brushes, first, by clamping them *very firmly* in their holders, so that they protrude to the proper length. Adjust them, secondly, so that they bear with a moderate but firm pressure on the commutator. See, thirdly, that when so pressing, they bear in the right positions. For 2-pole dynamos the brushes should bear on precisely opposite bars of the commutator. For 4-pole dynamos they bear on bars that are a quarter of the circumference apart. (It is customary for makers to mark two of the commutator bars with a centre-punch so that this adjustment may be verified.) In the row of two or more positive brushes abreast, arrange them so that the gaps between them are opposite the negative brushes, so that the commutator will wear evenly. (It is well to shift the position of the brushes along the brush pillars from time to time.) Then, having verified these adjustments, remove all spanners and loose pieces of iron from the vicinity of the field-magnets. If there is any fear of the dynamo being started in the wrong direction, it is well that the brushes should be only lowered after starting. It is dangerous to raise the brushes while the current is on.

It is necessary that carbon brushes should be very carefully fitted to the curvature of the commutator. One way of doing this is to paste round the commutator a strip of fine glass-paper and run the dynamo with the brushes in their normal position, until the ends are worn down to the right shape. Carbon brushes give less trouble than copper brushes, as they do not wear the commutator so much nor do they spark so readily. A carbon brush should be free from the slightest suspicion of a crack or flaw, and a "glass-hard" corner should not be allowed to come in contact with the commutator.

The brushes being adjusted and lubricators filled, see that the connexions are right, and the terminals tightly screwed down. Bring the machine up to speed slowly, keeping a sharp look-out for anything that may be wrong, and be ready to slow down at any instant. Do not raise a brush without having turned off the current, unless there are two or more brushes side by side. If the machine is shunt-wound it will at once excite itself, though the main switch is still open. If the dynamo is for supplying glow-lamps, do not on any account turn on the main switch until you see whether the machine is giving the right volts, or you may ruin all your lamps. For if the speed is too high, the volts may be too high. A pilot lamp or a voltmeter will tell you if all is right. Then, before you turn on the main switch, observe the brushes to see if there is any sparking. If there is any sign of sparks, rock the brushes forward or backward till a sparkless place is found. Not until then should the main switch be turned and the lamps lit. In the case of new machines it is well that they should be run unexcited for some hours, in order to wear the brush faces to fit the commutator truly.

Daily Attention.—It is of the utmost importance to keep a dynamo scrupulously clean. A cotton rag should be used in preference to *waste*, as the latter leaves loose ends sticking to parts where it is objectionable. An air-blast is used by the Westinghouse Co. for getting rid of dust. Besides daily lubrication, attention must be given to the brushes to see if they require to be fed forward or trimmed. The commutator should not be oiled, but only wiped with a clean oily rag or a piece of cotton cloth (*not waste*) smeared with vaseline. (This reservation does not apply to arc-light dynamos with special commutators with wide air-gaps, which may be oiled freely.) Do not let the oil creep on parts that do not require it. Oil is apt to spoil the insulating materials by rotting the varnish, and affording a lodgment for dirt and for the fine dust that flies from the brushes. Also, if oil gets to the commutator it will char under the brushes, forming a carbonaceous film between the commutator bars, inviting a short-circuit. This fault is less likely to occur when mica-insulation is used than when paper insulation is employed. It has been observed that the brushes wear and heat unequally: the positive brush wearing faster than the negative. But this is unimportant. If there is solder on the brushes, care should be taken that the soldered part should never be used for contact on the commutator; it will set up flashing sparks.

If the dynamo is driven from heavy shafting, so that there is no risk of turning backwards at starting or stopping, then the brushes may always be left down on the commutator. Many dynamos will spark at full-load unless the brushes are rocked forward beyond the point that gave sparkless running on open circuit. Sparkless running is a vital matter if the commutator is to last long. The attendant cannot be too strongly impressed with the necessity of proper care on this matter. A well-designed modern dynamo, if properly attended to, will soon acquire a beautiful dark-polished surface on its commutator. But the commutator, even of a good machine, may be ruined in a few hours by careless or ignorant handling. If the brushes press too heavily it will become scored or ploughed up. If they press too lightly, or if there is vibration that causes them to jump, or if they are allowed to spark, the commutator will be worn away in patches at the edges of some of the bars, and lose its cylindricity of outline. The only remedy in this case is carefully to turn it or file it down true; this should occur very rarely. Another occasional fault is a high segment in a commutator, caused by some inequality of expansion, or imperfect manufacture. Sometimes this can be cured by judicious hammering with a wooden mallet, or, failing this, by filing down. A special form of commutator-grinder, for trueing commutators that have worn irregularly, is described in the *Electrical Review*, July 24, 1903, p. 139. Another method is to place a long strip of glass-paper under one of the brush-sets, and holding the ends of it in the hands, to press it as in Fig. 573 against the commutator while the latter is kept slowly revolving. Emery is inadmissible; but carborundum paper has the advantage over glass-paper that it cuts the mica slips equally with the copper segments.

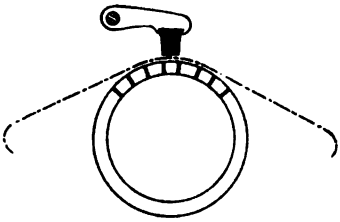


FIG. 573.

In central stations, and in all cases where reliability of supply is imperative, the insulation should be tested every day. If the insulation resistance of any part has seriously fallen (even though it may still seem sufficiently great) the machine should not be started until the cause has been ascertained and removed. A daily insulation test gives very good indication of the dryness and cleanness of the machine.

DISEASES OF DYNAMOS.[1]

At least four-fifths of the mishaps and breakdowns that occur with dynamos arise from causes more strictly within the province of the engineer than in that of the electrician. On the other hand, many of the mechanical faults that develop themselves in the machine might have been avoided had the engineer been possessed of a better knowledge of the electric and magnetic conditions which obtain in the running of the machine. It is not often nowadays that armatures fly to pieces. That disaster has seldom occurred since good engineers took in hand the construction of dynamos. The points which it is difficult for the ordinary engineer to grasp are the mechanical stresses on the copper conductors due to the magnetic field, and the necessity throughout of preserving proper insulation. All insulation being mechanically bad, he is apt, in attempting to give mechanical strength, to use the insulating materials in some way that vitiates their adequacy. For want of full electrical information he may apply the insulation in an erroneous manner and produce a dynamo which will break down under the severe conditions of actual work.

Burning-out of Armatures.—Single coils of an armature sometimes get heated to redness and burn the insulation. Sometimes a whole armature will become overheated, producing a general charring. The latter case happens more often to the armatures of motors than to those of dynamos. For if any excessive current is drawn by accident from a dynamo, the torque on the armature will generally become so great as to throw off the belt or pull up the engine. Whereas, with a motor, if the armature is jammed so that it cannot turn, an enormous current will continue to flow through it if the supply be not cut off. This is one reason for the overload cut-out device on motor starters.

Short-circuits in Armatures.—A short-circuit in the armature is usually first brought to notice by the smell of burning varnish. The machine should be shut down at once, and the armature felt all over with the hand. The short-circuited windings can generally be detected by their high temperature, even if the varnish is not visibly frizzled. If the greater part of the armature is short-circuited the fault is not so easily located by the rise in temperature. If an independent source of current is available, a very good plan is to pass a strong current between two opposite bars of the commutator, and compare the drop in potential between the different pairs of bars. An intelligent application of Ohm's law will generally lead to the discovery of the fault or faults. For instance, we know that if the armature is perfectly sound the fall in potential on each side of the leading-in point will be the same, so that a galvanometer whose terminals are attached to commutator bars at equal distances on each side of the leading-in point will show little or no deflexion. As one passes from bar to bar the occurrence of a great deflexion will immediately point to a want of symmetry at that point. The cases that might arise are so numerous that it would be useless to attempt an exposition of all of them. The experimenter must trust to his previous electrical training and the application of common sense. Where there are faults to the ironwork of the armature a current may be passed from one of the commutator bars to the ironwork, and a similar investigation made of the drop in potential between different bars. Another method is to connect all the bars of the commutator together by winding wire round it and then passing a current from this wire to the ironwork. The armature will become magnetized, the poles being in the vicinity of the faults. Methods of locating defects in drum armatures are described in the *American Electrician*, xii. p. 179, 1900. It may happen that in the repair of an armature, or the re-winding of a burned-out section, the workman, if unskilful, may reverse the connexions of the section. That section would then generate a reversed voltage, and reduce the voltage of the whole machine below its normal value.

---

[1] See paper by the author in *Electrician*, xx. 82, 1887; see also articles in *Elektrotechnische Zeitschrift*, xi. 186, 1890; *Electrical World*, xiv. 99, 184, and xviii. 303, 1891; Crocker and Wheeler, *Practical Management of Dynamos and Motors* (Van Nostrand, New York); Lummis-Paterson, *Management of Dynamos* (Crosby Lockwood and Son, London); Parkhurst, "Diseases of Dynamos," *Trans. Amer. Inst. Elec. Eng.*, 1894.

A short-circuit between an imperfectly insulated wire and the iron core beneath it is a fruitful source of trouble. Not that any *one* such contact can of itself produce any effect: but that if there is one such contact, then, if a fault occurs anywhere in the lamp circuit, there will at once be developed a serious leak through earth. Also the risk of shock to persons casually touching any part of the circuit is greater if there is any single fault in the dynamo. Some firms—chiefly American[1]—prescribe that the dynamo-frame itself should be insulated from the ground. The author's experience leads him to prescribe that the framework of the dynamo should on the contrary, be carefully connected to earth. If this is done, the risk of accident to attendants—which is considerable in the case of high-voltage machines insulated from their bed—is reduced to a minimum. A contact between an armature conductor and the iron core may occur because of the iron laminæ becoming loose and wearing through the layers of insulation. If the insulation is not waterproof and has got wet, it may break down when the machine is run. Sometimes armatures are destroyed by the burning of the insulation, by the overheating, not of the conductors, but of the iron core. In such cases the core has not been properly laminated. The burning of binding wires, which occasionally occurs, is due to want of compliance with the sufficient and necessary electrical conditions.

---

[1] The lightning-arresters used on many dynamos in the States are themselves a source of mishaps. If the dynamo-frame is properly earthed there is no need of a lightning-arrester on the dynamo. Efficient lightning-arresters should be fixed outside the dynamo-house where the overhead circuit enters it.

Being pieces of running machinery, dynamos are liable, as all engines are, to heating of bearings, if proper attention is not paid to lubrication and to the avoidance of needless dirt.

Fracture of Connexions.—This most annoying fault—the fracture of the connecting pieces which lead down from the armature conductors to the bars of the commutator—appears to be partly mechanical and partly electrical. These connecting pieces pass through a partial magnetic field, and they carry at times strong currents, which are reversed twice in each revolution. Hence they are each racked by lateral forces as they rotate, and this incessantly repeated breaks them off at last. The cure is either to make them mechanically very strong, or of stranded material, or to arrange that they shall lie outside the stray field.

Disconnexions in Armature.—Sometimes a disconnexion occurs where the armature conductors or windings are coupled up or connected down to the commutator. The evidence of this is (i.) a sparking that cannot be stopped by rocking the brushes forward or backward, and (ii.) one or more of the bars of the commutator appearing as if burned at the edge. One way[1] of finding the location of such a fault is to run the dynamo very slowly on short-circuit. Then after a few minutes' run stop the machine and see if any of the joints of the connectors are hot; this will indicate a partial disconnexion. If any entire coil is found to be hot, that is evidence not of a disconnexion, but of a short-circuit. Any disconnected coil in an armature is very easily found by the fall in potential method mentioned above. If the fault cannot be remedied at once, and it is necessary to run the machine, the bar belonging to the faulty coil may be connected to the succeeding bar by a blob of solder to stop the excessive sparking and preserve the continuity of the armature.

---

[1] Another way, applicable only to drum armatures, is due to Loomis (*Electrical Engineer*, New York, December 1891), and consists in holding the armature by hand and slowly turning it round against the torque while supplied with a current from some external source. If a position is found where it is easier to turn, it is clear that in this position the disconnexion stops part of the current so that the fault can at once be found by tracing the connectors which run from those bars of the commutator which are at the brushes in this position.

Defective Centring of Armature.—If by reason of wear of the bearings or misplacement of the magnet frame, the armature is decentred, so that the poles are unequally distant from the armature, there will be unequal forces mechanically, and the different circuits in the armature will be compelled to carry unequal currents, causing undue heating and sparking at the brushes. For bipolar machines, and for four-pole tramway motors the armature is sometimes purposely decentred a little above the level, in order to relieve the weight on its bearings. This must never be permitted with any machine in which there are more than two paths through the armature. To ensure good centring a small wedge, graduated on the face with marks, for insertion into the air-gap, is a useful appliance.

Flats in the Commutator.—Occasionally one of the commutator segments will become burned away or worn down to a lower level than the rest, or two adjacent bars may be similarly affected, causing a flat part on the cylindrical surface. Various suggestions have been offered to explain the origin of flats. If one of the bars was of unusually soft copper it might wear away faster; but the occurrence is unlikely. A partial disconnexion in the armature at the part connected to the particular bar of the commutator will give rise to a spark here at every half-revolution, so biting away this bar. Flats have been noticed also to spread along the bar from a flaw at one spot.

Another undoubted cause of flats is a mechanically weak or defective means of driving. If an armature, attached by a three-legged spider, is mounted on a weak shaft that bends, it is possible that periodic vibrations may occur which will cause the brushes to jump and set up sparks at definite points around the commutator. With well-constructed armatures, well-balanced and running without vibration, there is little fear of flats if the pressure of the brushes is sufficient. Whenever a bar of the commutator shows signs of burning along its edge, steps should at once be taken to prevent the development of a flat. A fine file should be applied to smooth the surface of the commutator in the neighbourhood of the threatened spot. Or, if need be, the commutator should be very slightly turned

° C.	90
5345	·0
7117	·0
9543	·1
484	·1
394	·1
827	·1
985	·2
399	·2
829	·2
761	·3
63	·4
104	·5
85	·6
68	·8
170	·9
387	1·2
42	1·5
36	2·0
54	2·5
31	3·2
41	4·2
39	5·7
83	8·3
06	10·2
73	13·
77	16·
28	23·
9	27·

60° C
·0569
·0718
·0905
·1141
·1440
·1816
·2290
·2887
·3641
·4592
·5790
·7301
·9206
1·1612
1·464
1·846
2·327
2·935
3·702
4·667
5·887
7·422
9·358
11·802
14·88
18·77
23·66
29·83

INDEX

TO

THE FIRST VOLUME.

A.

PAGE
ACCUMULATOR Charging, Dynamos for 64, 346, 722
„ Automatic Boosters for 796
Achard, on Motor Efficiency 800
Active Belt, Definition of 575
Activity of Motor 799
Adams, W. G., on Dynamo Tests 926
Adjusting Shunt for Over-Compounded Machines .. 319, 531, 697
Adjustment of Brushes 500
Admiralty Specification as to Temperature-Rise 914
Ageing of Iron 108
Air, Permeability of 81
Air-Blast for Cleaning 932
„ for Spark-Prevention 747
Air-Friction 520
Air-Gap in Magnetic Circuit 91, 109, 143, 150
„ Average Flux-Density in 545
„ Calculation of 92, 109, 150
„ Determination of Width of 153, 550
„ Distribution of Field in 214, 216
„ Effect of Widening 255
„ Gap-Coefficients 92, 143
Alioth & Co., Electrolytic Generator 720
„ Winding Pole Cores 174
Allgemeine Elektricitäts Gesellschaft, Armatures of .. 56, 461
„ „ „ Double-Current Machine by 761
„ „ „ Generators of 669
„ „ „ Motors of 856
„ „ „ Regulator of 873
"Alliance" Machine 13
Alloys used for Rheostats 902

PAGE
Alteneck, F. von Hefner, Dynamometer .. 917
„ „ Drum-winding .. 19, 23
Alternate Currents } (*see* Volume II.)
Alternators }
Aluminium, Reduction of .. 707, 709
„ Steel, Properties of .. 87, 100
„ used for Brush-holders .. 507
"Ambroin" .. 189, 488
Amortisseur .. 267
Amperage .. 545
Ampère, A. M., on Early Dynamo .. 9
„ Rule for Direction of Electromotive-Force .. 37
Ampere-Conductors .. 259, 541
Ampere-Turns .. 73, 77, 78
„ Calculation of .. 87, 111, 141, 148, 580
Analogy between Magnetic and Electric Circuit .. 75, 79
Angle of Lead of Brushes .. 213, 216, 238, 260
„ of Polar Span .. 261, 541, 568
Angular Speed .. 227, 282
Annealing of Iron .. 83, 90
Anti-friction Bearings .. 474
Apparent Flux-Density in Teeth .. 145, 545
„ Resistance of Armature .. 217
Appold's Improvement of Prony Brake .. 915
Apportionment of Losses in Generators .. 552, 553
„ „ in Motors .. 860
Arc, Electric, Instability of .. 347
Arc-Lighting Dynamos, Brush .. 330, 733
„ „ Features of .. 726
„ „ Thomson-Houston .. 742
„ „ Westinghouse .. 56, 748
„ „ Wood's .. 749
Armatures, Balancing of .. 469
„ Bar .. 442, 446
„ Barrel-wound .. 448
„ Binding of .. 439
„ Burning out of .. 934
„ Closed Coil .. 52, 201, 208, 350
„ Coils of .. 350, 442, 454, 462
„ Connecting up of .. 446, 448, 462
„ Core of .. 57, 422, 428, 436
„ Compensating .. 270
„ Cooling Surface of .. 186, 187, 559
„ Definition of .. 4, 48
„ Diameter of .. 536, 541
„ Disk .. 54, 56, 416

PAGE

Armatures, Design of .. 554
„ Drum .. 54, 55, 352, 387, 444
„ Equalizing Rings in .. 412, 665, 709
„ Exploration of .. 203, 935
„ Faults of .. 934
„ Gyrostatic Action of .. 468
„ Heating of .. 186, 552, 559
„ Iron in .. 57
„ Length of Core of .. 536, 540
„ „ over-all of .. 460, 575
„ Losses in .. 186, 552, 553, 559
„ Magnetic Density in .. 545
„ Number of Circuits in .. 199, 358, 369, 383, 407, 516
„ Open Coil .. 53, 728
„ Pole .. 54, 56
„ Practical Construction of .. 422
„ Reaction of .. 208
„ Resistance of .. 515, 614
„ Ring .. 54, 352, 410, 686, 710, 720
„ Spiders .. 428, 433, 640
„ Support of .. 428
„ Surface, Estimation of .. 559, 576
„ Teeth, Flux-Density in .. 144, 153, 154, 545
„ „ Shapes of .. 425
„ Temperature Rise in .. 186, 559, 635
„ Torque of .. 227, 230, 808, 817, 916
„ Ventilation of .. 186, 438, 635
„ Winding, theory of .. 350
„ Wire-wound .. 442, 453
Arnold, Professor E., on Adaptations of Wave-windings .. 408
„ „ on Commutator Losses .. 520
„ „ on Equalizing Connexions .. 415
„ „ Formula for Commutator Heating .. 520
„ „ on Pre-determination of Dispersion .. 141
„ „ on Reduced Diagrams .. 415
„ „ Rule for Number of Commutator Segments 483
„ „ on Series-Parallel Winding .. 369
Arnold & Mie, on Theory of Commutation .. 251
Arnoux, on Disk-winding .. 418
Asbestos .. 189, 193
Asphaltum .. 189
Auerbach, F., on Theory of Dynamo .. 32
Automatic Boosters .. 786
„ Regulators .. 871
Automobiles, Motors for .. 863
Average Electromotive-Force .. 281

PAGE
Ayrton, *W. E.*, on Armature Reaction 258
„ „ on Dynamo Testing 916
„ „ on Power Transmission 800
Ayrton & Perry, on Brake Dynamometer 917
„ „ Constant-Speed Motors 835
„ „ Motor 34
„ „ on Magnetic Shunts 138
„ „ on Sparkless Commutation 258
„ „ on Spurious Resistance 218
„ „ on Transmission of Power 800

B.

BACK Electromotive-Force (*see* Counter Electromotive-Force).
Backward Lead of Brushes 66, 259, 825
Baily, *F. C.*, on Rotational Hysteresis 106
Baker, on Self-Exciting Machine 16
Baking and Drying Armature Coils 454
„ „ Commutators 493
Balancers or Equalizers 776
Balancing of Armatures 469
„ Connexion for Compound Dynamos 320, 928
Ball Bearings 474
Bar Armatures 442, 446
Bars of Commutator (*see* Commutator).
Barlow's Rotating Wheel 33
Barrel-Winding 448
Barrett, *W. F.*, on Magnetic Properties of Iron Alloys .. 87, 100
Bate, *A. H.*, on Motor Starters 846
Bearings, Dimensions of 469
„ Pressure on 467
„ Self-Oiling 476, 478
Bedding of Wires 163
Bedplates 479
Bending Stress on Shaft 472
Berlin Central Station Dynamos 404, 687
Binding Wires 439
„ Calculation of 440
Bipolar Dynamos 20, 23, 115, 621, 675
Bitumen 189
Blathy, *O. T.*, on Secondary Losses 219
„ Test of Iron 85
Blood, on Design 538
Bobbins of Field-Magnets 164, 172, 178, 665

PAGE
Booster, Automatic or Reversible 780, 786
Bosanquet, R. H. M., on Magnetomotive-Force 76
Brackett's Method of Measuring Power 295, 919
Bradley's Arc-Light Dynamo 748
Bradwell, J., on Dynamos 542
Brake for Measuring Power 915
„ for Motors 915
Branched Magnetic Circuits 138
Breadth of Brushes 239, 248, 251, 550
Breguet, Antoine, on Theory of Dynamo 6
Brett's Self-Exciting Dynamo 11
Bronze used for Binding Wires 440
Brown, Charles E. L., Barrel-winding in Two Layers 448
„ „ Contributions to Dynamo Engineering 30, 659
„ „ Electro-metallurgical Dynamos .. 609, 709
„ „ Four-pole Dynamo 28, 662
„ „ Homopolar Dynamo 769
„ „ Method of Piling Coils 173
„ „ Methods of Mounting Core-Disks .. 430, 431
„ „ Pierced Core-Disks 431
„ „ Vertical Shaft Dynamos 31, 662
Brown, Boveri & Co. (see also Brown, C. E. L.).
„ „ Double-Current Machine 659
„ „ High-Voltage Dynamo .. 402, 549, 753
„ „ Method of Attaching Commutator Risers .. 496
„ „ Normal Type of Generator 659
„ „ Steam Turbine Dynamo 759
Brown, E., on Heating of Magnet Coils 184
Brooke, Charles, his Definition of term *Dynamo-Electric Machine* 1
„ „ on Wilde's Magneto-Electric Machine 14
Brush, Charles F., Arc-Lighting Dynamo 733
„ „ Commutator 735
„ „ Electro-plating Dynamo 706
„ „ Induction sheath 733
„ „ Regulator 740, 873
Brushes for Collecting Current 48, 235
„ Carbon 240, 254, 498
„ Care of 502, 931
„ Copper 241, 497
„ Current-Density in 241, 498
„ Lead of 213, 216, 238, 260
„ of Arc-Light Dynamo 497, 736, 745
Brushes, Pressure of 242, 504
„ Position of 259, 500, 737, 745, 825, 931
„ Resistance of Contact of 240
„ Setting of 500

PAGE
Brushes, Thickness of 239, 248, 251, 499
Brush-Holders 501, 504
,, Rocker, Design of.. .. .. 501, 509, 512
,, Sets, Increase of 406
,, ,, Number of 358, 404, 482
,, ,, Reduction in 405
Burning-out of Dynamos 934
Burstyn, on Parallel Running 927
Bushed Pole 268

C.

Cabanellas, on Spurious Resistance 218
,, on Demagnetizing Effect of Eddy-Currents 223
Calculations of Binding Wires 440, 441
,, of Coil-winding 148, 167, 580
,, of Efficiency 521
,, of Magnetic Circuit 108, 148
,, of Size and Output 535
,, of Wires of Rheostats 900
Carbon Brushes 240, 498
,, Resistances 873
Cardew, *Major P.*, on Dynamo Testing 920
Carhart, *Henry A.*, on *Jacobi's* Law 808
,, ,, on Magnetic Dispersion 138
Carpentier, *J.*, on Brake Dynamometer 917
"Carton Lyon" 194
Cast-Iron, Magnetic Properties of 83, 85, 87, 88, 90
,, for Pole-Shoes 127, 263, 686
,, for Yokes 128, 545
Cast-Steel, Magnetic Properties of 84, 89, 98, 100
Causes of Sparking 235, 250, 255
Caustic Soda, Manufacture of 703
Centrifugal Forces on Armatures 439, 468, 757
,, Governors 830
C.G.S. Magnetic Units 71, 78, 81
Characteristic Curves 321
,, ,, Drooping 330, 346, 749, 927
,, ,, External 326
,, ,, Internal 343
,, ,, of Motors 813, 818, 837
,, ,, No-load 524, 587, 602, 615, 626
,, ,, Pre-determination of 343
Chatwood on Motor Equipments 846
Chord-Winding 353

PAGE
Circuit, Magnetic, Calculation of 108, 148, 580, 585, 600
,, ,, Principle of 74, 76
Circuital Distribution of Vectors 75
Circulation of Power 921
Clarke's Early Dynamo 10
Clausius, R., Theory of Dynamo 32
Claw-Magnets 122
Cleaning Dynamos 932
Clerk Maxwell (*see Maxwell*).
Closed-Coil Armature 52, 201, 208, 350
.. Number of Paths Through 359, 404, 407
,, Two Paths Through 53, 201, 359
Coefficient of Dispersion or Magnetic Leakage 131, 137
,, of Self-Induction 218, 251, 273
,, of Transformation 775
Coercive-Force 96
Coils, on Armature 350, 442, 454, 462
,, Edge-Strip Winding 163, 183
,, Former-wound 454, 463
,, on Field-Magnet 172
,, Insulation of 175
,, Rules for Winding 164
,, Methods of Attaching 177
Collars on Shaft 472, 473
Collecting Rings 3, 660, 762
Combined Plant 925
Commercial Efficiency 297, 298
Commutation, the Act of 236
,, Diameter of 213, 216
,, with Fixed Brushes 239, 244, 827
,, Frequency of 273, 274
,, in Motors 824
,, Ratio 277, 608, 631
,, Theory of Reversing Field 238, 261, 825
,, ,, of Contact Resistance 240, 827
Commutator Bars or Segments 45, 481, 482, 486
,, of Berlin Dynamos 464
,, Calculation of Taper of Segments of 486
,, Care of 485, 931, 933
,, Design of 485
,, Distribution of Potential at 215
,, Energy Losses in 520
,, Flats in 937
,, of Ganz's Marine Generator 689
,, Insulation of 486, 487
,, Invented by Sturgeon 10

PAGE
Commutator, Lubrication of 932
„ Material of 486, 487
„ of Open-Coil Dynamos 735
„ Proper Number of Segments in .. 53, 482, 483, 556
„ Peripheral Speed of 484, 485, 757
„ Risers 494
„ for Rectifying 735
„ Size of 484
„ Sparking at 216, 235, 255
„ of Tramway Generator 676
„ of Tramway Motor 489
„ Ventilation of 488
Commuting Coils 270
„ Fringe 570, 693
Compagnie de l'Industrie Électrique (*see Thury*).
Compensated Armatures 270
Compensating Ampere-turns 259, 526, 588
Compound Dynamos, Design of 563, 571, 588, 595
„ „ Winding of 318
„ Winding 308, 314, 318, 348
„ „ Calculation of 318, 588
„ „ Differential 786
„ „ Experimental Determination of 319
„ „ in Motors 832
„ „ Slow in Action 107
Compounding, Curve of 349
Compressed-Stranded Wires 25, 160, 444
Compression, Effect of, on Magnetization 94
Concatenation of Machines 12
Concentration of Field 267
Condensers used in Sparkless Commutation 756
Conductors, Calculation of Number of, in Armature 549, 556
„ Current-Density in 545, 903
„ Drag on 223, 226
„ Eddy-Currents in 219, 442, 443, 444
„ Embedding of 226
„ Kinds of, on Armatures 441, 444
„ Lamination of 160, 444
„ Moved in Magnetic Field 7, 37, 281, 443
Connecting up Armature Conductors, Theory of 350, 354
„ „ „ Practical Methods of .. 444
„ Magnet-Coils 178
Connectors at End of Armature 355, 446, 448, 463, 495
„ to Commutator 494
„ Radial (*see* Risers).
Consequent Poles 117
Constant Current 67, 305, 726

PAGE
Constant Current, Dynamos for 726
„ „ Motors for 818, 823
„ „ Regulators for 727, 873
Constant Electromotive-Force 307
„ Speed in Dynamos 306
„ „ in Motors 831
„ Torque 818
„ Voltage 67, 304
„ „ Dynamos to Give 307
„ „ Regulators for 304
Constants used in Designing 545
Constantan 902
Construction, Practical, of Armatures 422
„ of Commutators 488
„ of Motors 857
Continuity of Current 11, 17, 51, 285, 287, 288
Controllers 885
Cooling Surface of Armatures 559, 683
„ „ of Commutators 520
„ „ of Magnet-Coils 169, 182, 184
Copal 189, 194
Copper, for Brushes, Current Density in 241, 498
„ Calculation of Wires 156, 164, 170
„ Deposition of 723
„ Heat-Losses in 181, 183
„ Refining of 707, 721
„ Secondary Losses in 219, 443
„ Specific Resistance of 156
„ Specific Utilization of 575, 701
„ Weight of 155, 171
Copper-Losses in Armatures 166, 515
„ „ in Rheostats 522
„ „ in Series Coils 181, 182
„ „ in Shunt Coils 169, 182
Cores of Armatures 57, 144, 422
„ „ to Find Proper Size of 536, 555
„ of Poles 125, 148
„ „ to Find Proper Size of 562
„ Segmental 58, 423
Core-Disks 57, 423
„ Insulation of 144, 423
„ Methods of Driving 428
„ Toothed 424, 859
„ Pierced 425, 431
Corsepius, Dr. M., on Designing of Slots 154, 567
Cost of Dynamos 572
Cotton Covering of Wires 193, 442, 454

Counter Electromotive-Force in Boosting 780
„ „ „ in Motors 744
Couple (*see* Torque).
Coupling of Dynamos 927
Couplings for Direct Driving 480
Creeping, Magnetic 107
Criteria of Good Design 276, 277
Critical Current 335
Resistance 332, 339
„ Speed 335
Crocker, F. B., on High-Voltage Dynamos 752
Crocker-Wheeler Co., Core-Disks 426
„ „ Machines 128
„ „ Motors 855
„ „ Motor-Generators 772
Crompton, R. E., Contributions to Electric Engineering 24, 33. 429, 924
„ on Eddy-Current Losses in Armature Conductors 444
„ on Stranded Conductors 25
Crookes, Sir W., on Wilde's Generator 14
Cross-Compounding of Dynamos 263, 757, 760
„ „ Déri's Method 267, 760, 791
„ „ Ryan's Method 265. 701
Cross-Connecting Armatures 409, 415, 460, 665
Cross-Magnetizing Reaction of Armature 208, 212, 258
„ „ Compensation for 263, 270
„ „ Estimation of 259, 261
„ „ in Motors 824
Current and Torque, Relation of in Generators 230
„ „ „ in Motors 811
Current-Carrying Capacity of Wires 167, 181, 183. 903
Current Density, Permissible, in Armatures 181, 545, 575. 860
„ „ „ in Brush Contacts .. 240, 498, 557. 634
„ „ „ in Magnet Coils .. 167, 183, 545, 665. 860
„ „ „ in Risers 545
„ „ in Electro-deposition 725
„ „ Effect on Heat Losses 181
Current in Conductors, Method of Indicating Direction of 211
Curves, Characteristic 321, 813
„ of Compounding 348, 523
„ of Efficiency 298, 522, 820, 925
„ of Magnetization 83, 98
„ of Saturation 112, 524, 615
Cutting of Magnetic Lines 7, 37, 226, 281. 444
Cycle of Magnetization 97
Cycles, Permissible Numbers of, in Designing 546, 566
Cylindrical Winding (*see* Barrel-winding).

D.

PAGE

Dalby, W. E., on Balancing Engines .. 467. 469
Dal Negro, his Early Machines .. 9, 33
Dampers, Magnetic .. 107, 267, 733
Data, Statistical, Analysis of .. 576, 700
Davenport's Motor .. 33
Davidson's Motor .. 33
Dead Turns .. 217, 290, 331
Definition of Dynamo-Electric Machine 1 (Footnote) and *see* Preface
Demagnetizing Effect of Armature .. 213, 256, 258
  „ „ Compensation of .. 270, 312, 832
  „ „ of Eddy-currents .. 223
  „ „ Estimation of .. 258, 259, 526
  „ „ in Motor .. 824
Density of Current (*see* Current-Density).
  „ of Magnetic Flux (*see* Flux-Density).
Deposition of Metals .. 723
Deprez Marcel, on Characteristic Curves .. 323
  „ „ on Compound Dynamos .. 348
  „ „ on Constant Potential Dynamos .. 32
  „ „ on Field-Magnets .. 118
  „ „ on Friction Dynamometer .. 915
  „ „ on Theory of Dynamo .. 32
  „ „ on Transmission of Power .. 34
Depth of Winding of Coils .. 171, 183
  „ of Slots, How to Fix Number of .. 560, 646
Déri's Method of Cross-Compounding .. 31, 267, 760
Derivation (*see* Shunt).
Design, on the Art of .. 532
  „ of Motors .. 850
  „ Order of Procedure in .. 533, 566
  „ Refinements in .. 567
  „ of Regulating Rheostats .. 900
  „ Rules for .. 544 to 563
Desrozier's Disk-Dynamo .. 31, 57, 418
  „ Magnetic Shunt .. 870
Dettmar, G., on Density of Flux in Cores .. 153
  „ on Iron Losses due to Distortion .. 924
Developed Winding Diagrams .. 356
Diacritical Current .. 114
Diameter of Commutation .. 46, 216
  „ of Shunt-Wire .. 168, 170
  „ of Wires (*see* Wire-Gauge Tables, Appendix).
Dielectric Strength of Insulating Materials .. 190
Differential Compound Winding .. 786

PAGE
Differentially-wound Motor 783, 832
Dick, on Flux-Density in Teeth 154
Dina, on Rotational Hysteresis 106
Direction of Current 211
  „ of Electromotive-Force 37
  „ of Magnetic Lines 72
Discoidal Ring Armatures 22, 29
Diseases of Dynamos 934
Disk Armatures 31, 56, 416
Disk Dynamo, Desrozier's 56, 418
  „ „ Faraday's 7, 766
  „ „ Fritsche's 31, 418
  „ „ Pacinotti's 56, 416
Disks for Armature Cores 57, 422, 427, 451, 859
Dispersion, Coefficient of 131, 137
  „ Increase at Full-load 141
  „ Magnetic 131
Distortion of Magnetic Field 208, 213, 215, 224
  „ Prevention of 262, 270
Distribution of Field in the Gap 208, 213, 226, 260
  „ of Flux in the Core 153
  „ of Potential at Commutator 203
Division of Yoke 129
Dobrowolsky, M. von Dolivo, on Bushed Poles 268
  „ „ „ on Inductor Machines 15
Double-Current Machines 762
Double Magnetic Circuit 115, 126
Doubly Re-entrant, Definition of 367
Drag on Armature by Field 223, 439
  „ on Conductors 223, 225
  „ on Embedded Conductors 226
Dredge, on Theory of Dynamo 6
Driving Horns 233, 439
  „ Spokes 233, 428
Drop-Forged Segments of Commutator 486
Drum Armature 19, 55, 352, 444
  „ „ with Barrel-winding 448
  „ „ with Evolute Connectors 446
  „ „ Reaction of 214, 257
  „ „ Winding of 352, 444
  „ „ with Wire-winding 445, 453
Drying an Armature 196, 930
Drysdale, C. V., Research on Measurement of Permeability .. 90
Du Bois, H., on Magnetic Properties of Iron 90
Ducts, or Air-ways, in Armature Cores 144
Dujardin's Early Machines 15

PAGE

Du Moncel, Count, his Early Work 13

Duncan and Hassen, on Dynamo Tests 926

Duplex Winding, Definition of 367

Dynamo-Electric Machine, or Dynamo, Definition of 2

„ „ „ Origin of Term (*see also* the Preface) .. 1

Dynamo-Electrische Maschine, Origin of this Term 17

Dynamo-Magneto-Electric Machine 17

Dynamometer 295, 915

Dynamometric Governor 830

E.

Ebonite 189

Economic Coefficient 297, 299, 303

Economy in Design 565, 575

Eddy Co.'s Electroplating Machines 720

Eddy-Currents 99, 104, 218

„ in Armature Conductors 219, 443

„ in Armature Mounting 23, 25, 218

„ Calculation of Losses due to 105, 517

„ in Core-Disks 99, 220

„ Demagnetization due to 219, 221

„ Law of 104

„ in Pole-Pieces 221, 517

Edge-wound Strip 163, 183, 666, 693

Edison Co. (*see General Electric Co.*)

Edison-Hopkinson Bipolar Dynamo 25, 111, 130

Edison, T. A., Early Dynamos 23, 115, 117

„ Regulator 307

„ Method of End-Connecting 447

Efficiency, Apportionment of Losses in 552, 559

„ Commercial, or net 297, 298

„ Curves of 298, 522

„ Definition of 298

„ Electrical, or Economic Coefficient 296

„ Estimation of 521

„ Gross, or Efficiency of Conversion 297

„ of Motors 799, 806

„ of Standard Dynamos 552

„ Testing of 914

Eickemeyer's Armature-winding 455

„ Dynamo 121

Electric Co., The (*see Allgemeine Elektrizitäts Gesellschaft*).

Electric Construction Co. 697

PAGE
Electric Energy .. 296, 521
Electrical Efficiency .. 297
Electrolytic Processes, Dynamos for .. 432, 703, 707
Electro-metallurgical Dynamos .. 432, 703, 707
Electro-deposition of Metals .. 703
„ „ Current-Density for .. 725
„ „ Voltage Appropriate for .. 724
Electromotive-Force Alternating .. 45, 284
„ „ Average .. 281, 284
„ „ Curve of .. 201, 207, 216
„ „ Factors of, in Dynamos .. 305
„ „ Fluctuations of .. 284, 288
„ „ of Moving Conductors .. 7, 37, 281, 767
„ „ Summation of in Closed-coil Armatures 201, 285
Electro-plating Dynamos .. 432, 703
Elkington & Co. use Electro-plating Machines .. 705
Elliptical Section, Formula for .. 125
Elmore's Electro-plating Dynamos .. 705
„ Homopolar Dynamo .. 770
Elphinstone, Lord, Early Dynamo of .. 24
Elwell-Parker Co. Motor-Generators .. 773
Embedding Conductors in Iron .. 25, 226
Emission of Heat at Surface .. 182, 187
"Empire Cloth" and "Empire Paper" .. 189, 195
Enamel .. 189
"Enamelac" Varnish .. 194
Enclosed Motors .. 854, 857
„ „ Heating of .. 185
End Connectors .. 446, 463
End-Play of Shafts .. 472
End-Plates for Core-Bodies .. 426
Ends of Coils, Modes of Fixing .. 174
Engine Speeds, Variation with Size .. 535
English Electric Manufacturing Co., Generator of .. 691
„ „ „ „ Motor of .. 858
Equalizer Connexions .. 409, 460, 709, 712
Equalizing Rings .. 412, 665, 709
Equations of Armature Windings .. 365 to 383
„ of Dynamo .. 281 to 320
„ of Motor .. 801, 811
„ of Motor-Dynamo .. 775
Equivalent Pole-Span .. 569
„ Ring-winding .. 386
Esson, W. B., on Armature Reaction .. 210
„ „ on Characteristic of Separately-Excited Machine .. 536
„ „ on Multipolar Machines .. 536

PAGE
Esson, W. B., on Output Coefficient .. 536
„ „ on Permissible Heating .. 182
Ettinghausen's Early Machine .. 10
Everett & Peake, on Commutation .. 246
Evolute Connectors .. 446, 460
Ewing, J. A., on Hysteresis .. 96
„ Hysteresis Tester .. 99
„ on Joints in Magnetic Circuit .. 93
„ on Magnetic Creeping .. 108
„ Papers on Magnetism .. 90
"Exciter" Machines, Design of .. 760
„ „ Examples of .. 673
Excitation, The .. 73
„ Calculation of .. 110, 148, 580, 614
„ Failure of .. 938
„ of Field-Magnets .. 91, 110, 148
„ Losses Due to .. 515
Exploring Distribution of Field in Gap .. 207, 213, 225, 260
„ Potentials at Commutator .. 203
„ Stray Field .. 135, 137
External Characteristics .. 326, 337
Extra High-Voltage Dynamos .. 752

F.

FAILURE to Excite .. 335, 938
Faults in Armature .. 934
„ in Field-Magnet Coils .. 938
Faraday, Michael, Discovers Induction .. 1, 7
„ „ Disk Dynamo .. 7
„ „ Homopolar Machines .. 7, 766
„ „ on Magnetic Circuit .. 75
„ „ his Primitive Forms of Dynamos .. 8
„ „ Researches on Magnetic Lines .. 37
Farmer, Moses, G., on Self-Excitation .. 16
Feathers and Keys .. 470
Ferranti & Co., on Edge-wound Strip .. 164, 183
„ „ on Heating in Strip Winding .. 183
Feussner, on Parallel Running .. 928
Field, Magnetic, Concentration of .. 207, 213, 225, 260, 568
„ „ Distribution of .. 267, 526
„ „ Stiffness of .. 255, 277, 545
„ „ Stray .. 130, 137
Field-Magnets, Advantage of powerful .. 61, 234

PAGE
Field-Magnets, Branched 138
.. „ Calculation of 148, 580, 611
.. „ Definition of 47, 48
.. „ Design of 263, 562, 570
„ „ Forms of 115
.. „ Formula for 110, 114
Field-Magnet Bobbins, Calculation of Heating .. 178, 183, 185
.. „ „ „ of Windings 148, 164, 168, 170, 580
.. „ „ Construction of 172, 665
„ „ „ Insulation of 175
.. „ .. Ventilation of 178
Fischinger's Design of Pole-Pieces 263
Fischer-Hinnen, J., on Armature Compensation 265
„ .. on Dynamo Losses 520
„ „ on Mechanical Losses 530
„ „ on Proper Number of Poles 546
„ „ on Rules for Fringing 150
"Flashing-over" 255
Flashing-Resistance for Motors 879
Flats on Commutator 937
Fleming, Prof. J. A., on Reluctivity 114
„ „ Rule as to Force on Conductors 223
„ „ Rule for Induction of Electromotive-Force 37
Fluctuations of Electromotive-Force 284, 288
Flux, Magnetic 73
Flux-Density, Apparent and Actual 146
„ „ Average 154, 545, 860
.. „ Calculation of 142
„ „ Definition of 73, 75, 81
„ „ Permissible Values of 545
„ Distribution of, in the Core 153
„ Magnetic, Definition of 73, 75, 81
„ „ Measurement of 137, 289
.. „ Regulation of 869
„ „ Stray 131
.. „ Useful 130
Fly-wheel, bolting Armatures to 473, 480
Forbes, Prof. George, Alternators at Niagara 31
„ .. on Calculation of Permeance 139
.. .. on Carbon Brushes 498
„ „ Homopolar Dynamo 767
Force on Conductor in Magnetic Field 223
Forces, Centrifugal 439, 468, 757
Formers for Winding Coils 173, 454
Former-wound Coils for Armatures 454
„ .. for Field-Magnets 173

PAGE

Formulæ for Armature Winding 350, 376–383
„ for the Electro-Magnet 110, 113
Foucault Currents (*see* Eddy-Currents).
Foundation-Ring for Armature 431
Foundations 930
Fractional Pitch 370
Frankfurt Exhibition Tests 926
Frequency of Commutation 273, 274
„ of Magnetic Reversals 100, 545, 546
Friction, Coefficient of, at Commutator 519
„ Loss of Energy due to 519, 639, 923
Fringe of Field 144, 569
Fringing, Allowance for 144, 150
Fritsche, on Armature Winding 418
Frölich, Dr. O., on Characteristics of Motors 823
„ on Eddy-currents 219
„ Equations of Electro-Magnet 114, 816
„ Researches on Theory of Dynamo 32
Froment's Early Motor 33
Froude's Brake Dynamometer 915
Fynn, V A., Field-Magnet 123
„ Armature Winding 253
Fundamental Equations of Dynamo 281, 282, 542
„ „ of Motor 811, 838, 852

G.

Gaisberg on Armature Distortion 207
Gallusser on Commutation 251
Ganz & Co., Attachment of Risers 495
„ Form of Slots 426
„ Marine Generator 269, 689
„ Method of Fixing Coil Ends 174
„ Space-Factor in Slots 162
„ Ventilating Pieces 438
Gap in Magnetic Circuit, Calculation of 92, 109, 150
„ „ „ Coefficients for 92, 143
„ „ „ Effect of 91
„ „ „ Width of (to find) 153
Gas-engines 702
Gaugain, J. M., Physical Theory of Dynamo .. .. ..
Gauge of Wire 167
„ „ Tables of (see Appendix).
Gauss, the (Unit of Intensity of Field) 72

PAGE
Gauze for Brushes 496
General Electric Co. (Schenectady) Fluxes in Multipolar Dynamo 156
" " " Generators 675
" " " Insulation of Magnet Coils .. 175
" " " Tramway Motors 859
German Silver 439, 494, 902
Gilbert, the (Unit of Magnetomotive-Force) 74
Girault, on Condition of Commutation 250
Glass 189
Gold, Deposition of 724
Goldsborough, Prof. W. E., on Distribution of Flux in Cores .. 153
" " on Stray Field 141
Gordon, J. E. H., Two-Phase Alternator 24
Governing by Steam-Pressure 505
" Dynamometric 830
Government of Motors 833
Gramme, Z. T., on Coupling Series Dynamos 928
" Dynamos 18, 24
" Motor-Dynamo 772
" his Ring Armature 18
Graphic Calculation of Equivalent Pole-Arc 569
" " of Excitation .. ..; 524 to 528
" " of Resistances in Regulators 529, 907
" Methods 111, 147, 321
" Theory of Dynamos 321
Graphite Brushes 498
Gravier, A., Shaped Poles 268
Gülcher Co.'s Brush-holder 491
Gun-metal used for Armature Spiders 429
" used in Commutator Construction 489
Gutta-percha 189
Gyrostatic Action of Armature 468

H.

Hadfield's Steel 87
Hagenbach on Theory of Dynamos 32
Hand Rules for Direction of Induced Currents 38
Hawkins, C. C., on Theory of Commutation 244, 251
Hay, A., on Form of Magnetic Lines 154
Heat, Effect of, on Insulation Resistance 190
" " on Magnetization 95
" " on Resistance of Copper 156
Heat-Waste in Armatures 515, 552

PAGE
Heat-Waste in Magnetization (*see* Iron-Losses).
Heath, on Homopolar Machines .. 770
Heating and Surface Emission (*see also* Temperature-Rise) .. 182
„ of Armatures .. 186, 515, 552
„ at Commutator .. 520
„ of Cores .. 99 to 105
„ by Eddy-Currents .. 105, 221, 517, 590
„ Estimation of .. 552
„ by Hysteresis .. 100, 590
„ in Insulation .. 190
„ of Magnet-Coils .. 182
„ of Pole-Pieces .. 222
„ of Wires in Rheostats .. 904
Hefner-Alteneck, F. von (*see Alteneck*).
Heldt, P. M., on Mechanical Stresses in Armatures .. 227
Hele-Shaw, H. S., on Form of Magnetic Lines .. 154
Henley's Early Inductor Dynamo .. 15
Henry's Motors .. 33
Henry, the (Unit of Inductance) .. 273
Hering, Carl, on Armature-Winding .. 351
„ „ on Homopolar Induction .. 771
„ „ on Magnetic Leakage .. 138
Herwig on Theory of Dynamo .. 32
Heteropolar Induction .. 766
High Voltage Dynamos .. 752
Historical Notes .. 7
Hjorth, Sören, his Machines .. 13
Hobart, H. M., Design of Tramway Generator .. 632
„ on an Armature Winding .. 460
„ on Cooling Surface .. 635
„ on Commutator-Speed .. 634
„ on Insulating Slots .. 193
„ on Standardization of Design .. 574
(*See also Parshall and Hobart*).
Holmes' Early Dynamos .. 13
Holtzer-Cabot Electro-plating Machines .. 722
Homopolar Dynamos .. 767
„ Induction .. 767
Hopkinson, Dr. J., on Armature Interference .. 260
„ „ on Characteristic Curves .. 25, 323
„ „ on Coefficient of Dispersion .. 111, 134
„ „ on Magnetic Calculations .. 25, 35, 110
„ „ on Magnetic Properties of Iron .. 83
„ „ Modification of Edison Dynamo .. 23, 24, 26
„ „ on Retardation of Magnetism .. 107
„ „ on Reversing Gear .. 830

PAGE

Hopkinson, Dr. J., on Testing Dynamos 918, 920
„ „ on Torque of Motors 819
Hopkinson, Drs. J. and E., on Dynamo Design 35
„ „ on Excitation by Backward Lead .. 259
„ „ on Magnetic Circuit 110
Horns or Pole-Tips 127
Horns, Driving 233, 439
Horse-Power of Dynamos and Motors 229, 296
„ Testing 915
Housman, on Armature Compensation 264
„ on Separation of Losses 922
Houston, E. J. (*and see Thomson-Houston*).
Hub of Armature 428, 433
Hummel, on Causes of Losses 769
Hunt, R., on Electromagnetism as a Motive Power 792
Hutin and Leblanc, Amortisseur 107, 267
Hysteresis, or Magnetic Fatigue 96, 99
„ Calculation of Loss due to 100
„ Constants of 99, 100
„ Increase of, with Time 108
„ Law of 99

I.

IDLE Coil 206, 238
„ Wire 55
India-rubber 189
„ and Asbestos (Vulcabeston) 189, 193
„ Hard (Ebonite) 193
„ Varnish (*Scott's*) 190
Induction of Electromotive-Force 7, 37, 281, 443, 767
„ Homopolar 766
Inherent Regulation 531
Input and Output 521
Insulating Materials, Classification of 189
„ „ Air 487
„ „ Ambroin 488
„ „ Armalac 190
„ „ Asbestos 58, 174, 193, 487
„ „ Canvas 175, 190
„ „ Cardboard 194, 195
„ „ Carton Lyon 194
„ „ Cotton 193, 442, 454
„ „ Ebonite 189

PAGE
Insulating Materials, Empire Cloth 195
„ „ Enamel 194, 423
„ „ Enamelac 190
„ „ Fibre, Hard White 441
„ „ Fibre, Vulcanized 190, 193
„ „ Film of Oxide 423
„ „ Fuller-board 561
„ „ Hard-rubber 175, 193
„ „ Indiarubber 189
„ „ Insulating Paint 194
„ „ Ivory 189
„ „ Japan 190, 423
„ „ Kieselguhr 194
„ „ Linen 192, 195
„ „ "Made Mica" 175
„ „ Manila Paper 189, 193, 561
„ „ Megohmite 194
„ „ Mica 175, 190, 191, 192, 441, 487
„ „ Micanite 190, 195, 487
„ „ Millboard 172
„ „ Muslin 175
„ „ Oil 189, 193
„ „ Oiled Linen 177
„ „ Oiled Paper 193
„ „ Paper 58, 194, 423, 464
„ „ „ Manila 193, 423, 561
„ „ „ Oiled 193
„ „ „ Paraffined 193
„ „ „ Parchmentized (Willesden Paper) .. 189
„ „ „ Shellacked 193
„ „ „ Varnished 195, 441
„ „ Papier-mâché 190, 488
„ „ Plaster 481
„ „ Porcelain 190
„ „ Press-spahn 172, 175, 190, 193, 487
„ „ Resin 194
„ „ Rope (Hard) 176
„ „ Rope-paper 194, 195
„ „ Rubber Varnish (Scott's) 190
„ „ Shellac 193, 194
„ „ Silk 189, 442
„ „ Slate 189, 193
„ „ Stabilit 194
„ „ Sterling Varnish 194, 442
„ „ Stoneware 190
„ „ Sulphur 189, 194

PAGE

Insulating Materials, Tape 174, 193, 196, 454, 561
„ „ Varnish 174
„ „ Vulcabeston 193
„ „ Vulcanized Fibre 172, 175, 190, 193, 441, 490
„ „ Water-Glass 194, 423
„ „ Wood 190, 193
Insulation of Armature-Bolts 428
„ of Armature Core-bodies 195
„ of Binding Wires 441
„ of Bobbins 172, 175
„ of Brush-Holders 502
„ of Commutators 487
„ of Core-Disks 57, 104
„ of Dynamo from Ground 935
„ of Equalizing Rings 664
„ of Former-wound Coils 173, 454
„ -Resistance 193
„ of Slots 161, 193, 195, 560
„ Tests 914
„ of Wires 164, 196
Intensity of Field 72, 79, 81
Interchangeability of Parts 850
Interference of Armature (*see* Armature Reaction).
International Electrical Engineering Co., Generator of 702
Iron, Magnetic Properties of Various Brands 83, 85
„ Ageing of 108
Iron Losses (*i.e.*, Waste of Power in Iron) 99, 516
„ „ Estimation of 100, 105
Iron Resistance for Rheostats 320, 903
Iron (*see* Armature-Cores, Flux-Density, Hysteresis).
Iron Wire used for Cores 54
Ironclad Type of Field-Magnets 120, 121

J.

Jacobi, on Back Electromotive-Force of Motors 31
„ his Early Dynamo 10
„ on Electro-Magnet 113
„ his Law of Maximum Activity 806
„ his Early Motor 33, 34, 793
Japan 191, 423
Jehl, F., on Continuous-Current Transformation 774
Jervis-Smith, Rev. F., Methods of Measuring Work and Torque 295, 910
Johnson & Phillips, Kapp's Bipolar Dynamo 439, 621

PAGE
Johnson, on Early Self-Exciting Dynamo 15
Joints in Magnetic Circuit 93, 115
Joubert, on Method of Exploring Distribution of Potential 204
„ on Spurious Resistance 217
„ on Theory of Dynamo 32
Joule, J. P., on Back Electromotive-Force of Motors 794
„ Early Motors of 31
„ on Electromagnet 113
Joyce, S. on Heating of Coils 185

K.

Kapp, Gisbert, Brush-Holder 503
„ on Calculation of Dynamos 25, 77, 110, 141
„ Commutator 490
„ on Depth of Winding 171
„ on Design of Dynamo 25
„ Dynamos 25, 120
„ on Formula of Electro-Magnet 113
„ on Magnetic Circuit 77, 110
„ Method of Driving Core-Disks 429
„ Method of Fixing Ends of Coils 174
„ on Output Coefficient 537
„ on Separation of Losses 921
„ on Testing Dynamos 921
Kelsey, W. R., on Gyrostatic Action 469
Kelvin, Lord, on Efficiency of Motors 799
„ „ on Theory of Dynamo 35
„ „ on Theory of Homopolar Dynamo 768
„ „ on Gyrostatic Action 468
Kolben & Co. Electrolytic Machine 718
„ Generators 669
„ Losses in Generators 553
„ Output Coefficient 538
„ Winding Scheme of Series-Parallel Armature .. 401
Kennedy, A. B. W., Test of Combined Plant 925
Kennedy, Rankine, Homopolar Dynamo 769
„ „ Iron-clad Dynamo 120
Kennelly, Prof. A. E., on Armature Reaction 258
„ „ „ on Reluctivity 114
Keys 479
Kieselguhr 194
Kiloline, Definition of 74

PAGE

Kingdon's Inductor Alternator .. 15
Kohlrausch, Prof. W., on Armature Distortion .. 207
Koosen, J. H., Early Researches .. 31
Krupp's Dynamo-Magnet Steel .. 85
Kruppin .. 902

L.

Lamb, G. C., on Permeability Measurer .. 90
Lamme, B. G., Balancing Windings .. 416
Ladd's Dynamo-Magneto-Electric Machine .. 17
Lag, Magnetic .. 108
Lahmeyer's Booster .. 789
„ Dynamos .. 132
Lamination of Core-Bodies .. 57, 99, 219
„ of Pole-Cores .. 220
„ of Pole-Pieces .. 220, 221
„ of Armature Conductors .. 160, 443
Lamont, on Law of Electromagnet .. 114
Lap-winding for Drums .. 360, 449
„ Examples of .. 377, 400, 666, 683, 753
„ Rules for .. 376, 383
La Société Cail, Extra High Voltage Machine .. 752
Lauckert's Compound Winding .. 33
Laurence, Scott & Co.'s Motor-Dynamo .. 773
„ „ Motor Controller .. 900
Lead of Brushes .. 46, 213, 216, 238, 260
„ „ Backward or Negative .. 259, 271
„ „ in Motor .. 825
Leakage, Magnetic .. 131
Leblanc (*see Hutin and Leblanc*).
Lecher, E., on Homopolar Induction .. 771
Ledeboer, on Parallel Running .. 927
Length and Diameter of Armatures .. 536, 539
„ of Air-gap .. 154, 550
Lenz, E., on Dynamo as Motor .. 31
„ on Electromagnet .. 113
„ Law of Reaction .. 31
„ Researches .. 31
Leonard, H. Ward, Method of Motor Control .. 849
Le Roux, on Theory of Dynamo .. 31
Lightning Arresters .. 935
Line, Neutral .. 216
Line-Integral of Magnetizing-Forces .. 78

PAGE
Lines, Magnetic 40, 72
Liquid Resistances 911
Load of Dynamo 521
„ of Motor 813
Locomotive Motors 861
"Lohys" Iron 85, 100
Lontin's Early Machines 19
Loomis, on Location of Armature Faults 936
Loss of Energy in a Magnetic Cycle 97
Losses Apportionment of 552, 553
„ in Copper 181, 183, 219, 443, 515
„ in Iron 99, 105
„ Separation of 922
Lost Amperes 300
„ Volts 292
Lubrication of Bearings 477, 932
„ of Commutator 932
Lummis Paterson, on Dynamo Management 934

M.

MAGNALIUM (Magnesium-Aluminium Alloy) 441
Magnets of Dynamos (*see* Field-Magnets).
Magnet Coils, Heating of 182
„ Cores, Average Flux-Density in 545
„ Steel 85, 89
Magnetic Calculations 108, 148
„ Circuit 74, 76
„ „ Air-gap in 91
„ „ Branched 113, 138
„ „ Calculation of 108, 148
„ „ Joints in 93
„ „ Reluctance of 81
„ Conduction 76
„ Creeping 107
„ Cycle 97
„ Dampers 107, 267
„ Dispersion 131
„ Field about Conductors 40
„ Flux 73, 75, 130
„ Leakage 131
„ Lines 40, 72
„ Permeability 81 82
„ Potential 80

PAGE
Magnetic Principles 71
„ Properties of Iron and Steel 83, 85
„ Pull on Armature 467
„ Shunt 138, 870
„ Units 71, 74, 81
Magnetization of Iron 83 to 96
Magnetizing Coil 77, 164 to 178
„ „ Calculation of 152, 168
Magnetomotive-Force 76, 78, 108
Magneto-Electric Machine or Magneto-Dynamo 1, 8, 47, 62, 290
Magneto-Ringer 47
Magnolia Metal 474
Malderen's Early Machine 13
Management of Dynamos 926
“Manchester” Type of Magnets 27, 28, 117, 263
Manganese Copper 902
Manganin 902
Manila Paper 189, 193, 561
Marble 189
Marshall, W. Bayley, on Anti-Friction Rollers 476
„ *W. R. V.*, Forms of Pole-Pieces 269
Mascart, on Theory of Dynamo 32
„ „ of Transmission of Power 799
Masson's Early Researches 13
Material, Specific Utilization of 575, 701
Mather, on Armature Compensation 264
Mather and Platt's Machines 25
Mavor, H. A., on Active Belt 575
„ on Bedding of Wires 164
„ on Costs of Dynamos 573
„ on Dynamo Design 573
„ on Stray Field 135
Maxwell, J. Clerk, on Self-Exciting Machines 32
Mechanical Actions and Reactions 223, 227 to 234
„ Characteristics 231, 810 to 824
„ Points in Design 439, 467, 851
Megaline, Definition of 74
Megohmite 189, 194
Menges, on Armature Compensation 264
„ on Dynamo-Testing 920
Meyer, H. S., Tests of Iron 85
„ on Tooth-Density 545
Meyer, on Theory of Dynamo 32
Meylan, on Parallel Running 927
Mica Sheet 175, 190, 191, 192, 441, 487

PAGE
Mica Canvas .. 191, 193
,, Cloth .. 191, 193
,, Paper .. 193
,, Proper Thickness of .. 191, 193
,, Shellacked (Micanite) .. 190
,, Moulded .. 487
Micanite (or "Made Mica") .. 175, 190, 195, 487
Mie, G. (*see Arnold & Mie*).
Mild Steel, Magnetic Properties of .. 84. 89
Millward, Early Application of Machine to Electro-plating .. 705
,, ,, Researches on Exciting Electro-Magnets .. 705
Minet, A., on Dynamo Tests .. 926
Mitis Metal .. 89
Moigno, Abbé, on Separate Excitation of Electro-Magnets .. 10
Moncel (*see Du Moncel*).
Mordey, W. M., on the Ageing of Iron .. 108
,, on Armature Exploration .. 205
,, on Armature Reaction .. 265
,, on Coupling Compound Dynamos .. 928
,, on the Drag on Embedded Conductors .. 227
,, Field-Magnets for Alternators .. 122
,, Inductor Alternators .. 15
,, on Motor and Dynamo Analogies .. 828
,, on Rotational Hysteresis .. 106
,, on the Shunt Motor .. 822
,, Method of Cross-Connecting .. 405, 409
,, ,, Winding Armatures .. 270
,, Multipolar Ring .. 409
,, "Victoria" Dynamo .. 28, 121, 410
Morin's Dynamometer .. 915
Motoring of Series Dynamos .. 347
Motors, Acceleration of .. 842
,, for Automobiles .. 863
,, Calculation of .. 850
,, Characteristics of .. 813, 818, 824
,, Commutation in .. 824
,, Direction of Rotation .. 795
,, Design of .. 850
,, Efficiency of .. 806, 820
,, Historical Notes on .. 33, 792
,, Lead of Brushes in .. 826
,, Multivoltage .. 840
,, Regulation of .. 838, 879, 885
,, Reversing-Gear for .. 830, 880, 891
,, Speed of .. 808, 810, 838
,, Theory of .. 800

PAGE
Motors, Torque of 808, 842, 852
Motor-Dynamos or Motor-Generators 772
Müller on Magnetization of Iron 113
Müller's Disk Winding 418
Multiplex Windings 367, 377, 397
Multipolar Generators, Notation of 6
„ „ Output of 540
„ „ Utilization, Coefficients in 701
Multipolar Series-winding (*see* Series Grouping).
Murray's Dynamometer 918
„ Tests of Brush Dynamo 740, 926
Murray, on Self-Excitation 16

N.

Neu, Levine & Havill on Heating of Magnet-Coils 184
Neumann, on Laws of Induction 31
Neutral Points on Armature 216
„ „ on Commutator 216, 239
Niaudet, Alfred, on Gramme Dynamo 18
„ „ on Theory of Dynamo 6
Nickel, Electro-Deposition of 725
Nickel Steel 902
Nickelin 902
Niethammer, F., on Heating of Enclosed Motors 185
„ on Stray Field 133
„ on Traction Generator 639
Noise in Running 938
No-Load Characteristic 524, 587, 602, 615, 626
„ Release for Motors 875
Nollet's Early Machines 13
Non-Concentric Poles 269, 700
“ Non-Polar ” Dynamo 767

O.

Oerlikon Machine Works, Armature Construction .. 430, 439, 447
„ „ Commutator Construction .. 490, 492, 493
„ „ Constants of Machines 701
„ „ Electrolytic Machines 432, 712
„ „ Generators .. .. 30, 651 to 659
„ „ on Heating of Armatures 187

PAGE

Oerlikon Machine, on Heating of Magnet Coils 183
„ „ High-Speed Generator 757
„ „ on Insulating Materials 190
„ „ Motors 861
„ „ Rule in Design 278
Ohm, Dr. G. S., Law of 38
Oil (*see* Lubrication).
Oil as Insulator 189
Oiled Paper 193
Oiled Linen 177
Open-Coil Armatures 53, 728
„ Advantages of 727, 747
Order of Procedure in Design 554, 566
Organs of Dynamos 44
Oscillatory Dynamo 23
Output in Relation to Size 535, 575
Output Coefficient, Esson's 537
„ „ Steinmetz's 538
Output Limited by Heating 533, 539, 700
„ „ by Sparking 533, 539
Over-All Length of Armature, Estimation of 460, 558
„ „ „ as Measure of Output 575
Over-Compounded Generators 318, 349, 595
„ „ Design of.. .. .. 563, 566, 595
Over-Load of Generator 630
„ of Motors 875
Over-Type of Dynamos, Support of Armature in 467

P.

Pacinotti, Professor A., Disk Dynamo 22, 416
„ „ his Early Dynamo 17
„ „ Motor 22
„ „ Toothed Core 18
Page, G. C., his Early Machines 11, 33
Paper, as Insulator (*see* Insulating Materials).
Papier-Mâché 190, 488
Paraffin Wax 189
Paraffined Compositions, Paper, Slate, etc. 193
Parallel-Wound Armatures 359, 365, 366
Parallel, Coupling Machines in 927
Parchment, Vegetable 189
Parker (*see Elwell & Parker*).
Parshall, H. F., on Apportionment of Losses 553

PAGE

Parshall, H. F., Curve for High Flux-Densities .. 85
„ „ Efficiency Curve .. 522
„ „ Multipolar Generators .. 677
Parshall & Hobart, Electric Generators .. 677
„ „ on Reactance Voltage .. 272
„ „ on Temperature-Rise of Commutators .. 520
Parsons, Hon. C. R., Steam Turbines, Generator for .. 759
„ „ Suggests Weights on Brushes .. 504
Passburg Vacuum Chamber .. 196
Pedestals .. 474
Peripheral Speeds of Armatures .. 187, 290, 535, 555, 701
„ „ of Commutators .. 484, 519, 520, 634
Permeability Curves for Iron and Steel .. 83 to 86
„ Variation of, due to Distortion .. 527
Permeance, or Magnetic Conductance .. 138
Permissible Heating of Armatures .. 182 to 185
„ „ of Commutators .. 520
„ „ of Magnet-coils .. 186
„ „ of Wires in Rheostats .. 901, 903
Perry, Professor John (see Ayrton & Perry).
„ „ Constant-speed Motors .. 835
„ „ Inventor of the Booster Method .. 778
„ „ Ring Winding .. 411
„ „ on Shaft Stresses .. 472
Petrina's Early Machine .. 10
Peukert on Armature Reaction .. 259
Phosphor-Bronze .. 439, 902
Picou, R. V., on Armature Interference .. 217
Pitch of Poles .. 540, 541, 633
„ Winding .. 353, 370
Pixii's Early Machines .. 9
Platinoid .. 902
Plücker's Homopolar Dynamo .. 766
Poggendorff's Researches .. 10
Pole-Armatures .. 54, 55
„ Core, Fixing Dimensions of .. 562, 638, 852
„ Pieces, Eddy-Currents in .. 23, 154, 221, 517
„ „ Lamination of .. 127
„ „ Saturation of, advisable .. 127, 545, 686, 689
„ „ Special Forms of .. 263 to 270, 571, 686, 691, 707
Polar Span, Angle of .. 150, 261, 547
Poles, Fixing Number of .. 545, 554
Poncelet's Brake .. 915
Porcelain .. 189
Postel-Vinay Co's. Generator .. 685
Potential, Magnetic .. 80

PAGE
Potential at Terminals 291, 293, 299, 301, 304, 310–317, 326, 336, 348, 644
Potier, A., on Armature Interference .. 217
Power of Dynamo .. 296, 521
Pressure on Bearings .. 467
Pressure-Drop, Calculation of .. 293, 524
Preston, T., on Homopolar Induction .. 771
Prevention of Sparking (*see* Commutation).
Procedure in Design .. 554, 566, 852
Prony Brake .. 915
Puffer, W. L., on Parallel Running .. 928
„ on Stray Field .. 138
Pull, Magnetic, of Poles .. 467
„ „ on Armature Conductors .. 223
Pulley, Overhung .. 470
Pulvermacher's Early Machine .. 10
Puncture Tests .. 192, 195

R.

RACING of Motors .. 818
Racking of Armature Conductors .. 223, 232
„ of Risers .. 494
Radial Depth of Core .. 561
Radial Diagrams of Armatures .. 362
Radian, or Unit Angle .. 228, 282
Raffard's Brake .. 915
Railway Motors .. 858
Ratio of Transformation .. 775
Ravenshaw, H. W., on Dynamo Testing .. 920
„ „ Spherical Bearing .. 477
Rayleigh, Lord, Method of Testing .. 913
Reactance-Voltage .. 272
Reaction (*see* Armature Reaction).
„ Brush-holders .. 508
„ Mechanical .. 223, 813
Rechniewski, on Continuous-Current Transformation .. 774
„ on Motor Characteristics .. 837
Rectangular Wires .. 25, 163, 168
Rectification of Currents .. 46, 51, 705, 750
Rectifiers .. 51, 750
Redressed Currents .. 51, 705, 750
"Reduced Scheme" of Wave-winding .. 415
Reducers .. 849
Reduction of Metals .. 707

PAGE

Re-entrant Windings .. 366
Regulation, Inherent .. 531
Regulators for Arc-Lighting Machines .. 747, 873
„ for Generators (*and see* Rheostats) .. 530, 907
„ for Motors (*and see* Controllers) .. 879, 909
Reignier, on Regulators .. 874
Reithöfer, on Armature Winding .. 351
Relation between Size and Output .. 535, 575
Reluctance, Magnetic .. 76, 110
„ Calculation of .. 109
Remanence .. 95
Residual Magnetism .. 95
Resistance of Armatures, to find .. 515, 913
„ at Brush-Contacts .. 240, 519
„ in Characteristic .. 331
„ of Coils .. 461
„ of Insulation .. 190, 193
„ for Regulating .. 63, 65, 306, 530, 900, 905, 911
„ of Shunt Coils .. 168, 304
„ Spurious, in Armatures .. 217
„ Variation of, with Temperature .. 156, 190, 515
„ of Wires .. 157 to 171, 900, 902
Retardation of Magnetism .. 96, 106, 733
Reversal, of Motor-Field .. 880
„ of Polarity .. 64, 346, 706
„ Prevention of .. 705
„ of Rotation .. 830, 880
„ Sparkless, in Commutation .. 235
„ Theory of .. 238, 240
Reversibility, Principle of .. 34, 792
Reversing Field, Theory of .. 238, 260, 276
„ Gear of Motors .. 830, 880, 891
„ „ Minimum Value of .. 265, 276
Rheostat, Calculation of Resistance for .. 530, 900
„ for Regulating Field .. 65, 307, 840, 907
„ Wires for .. 901
Right-Hand Rule .. 37
Right-Handed Winding .. 351
Ring Armatures, Cross-Connexion of .. 409
„ „ External, in Berlin Dynamos .. 21
„ „ Gramme's .. 18
„ „ History of .. 18
„ „ Magnetization of .. 209
„ „ Pacinotti's .. 17
„ „ Series-Parallel Winding of .. 381
Rise of Temperature (*see* Temperature).

PAGE
Ritchie's Early Machines 10, 33
Robertson on Armature Winding Theory 351
Rocker-Ring 509, 715
Rockers 48, 501, 509, 715
Rocking of Brushes 510
Röhr, on Annealing Iron 90
Rotational Hysteresis 106
Rothert, Alexandre, on Apportionment of Losses 36, 553
„ „ on Former-wound Coils 466
„ „ on Output Coefficient 542
„ „ on Procedure in Design 566
„ „ on Space-Factor in Coils 161
Rowland, Professor H. A., on Magnetomotive-Force 76
Rücker, Sir A. W., on Limits of Regulation 35
Rupp, on Continuous-Current Transformation 774
Ryan, Professor H. J., on Armature Compensation 207
„ „ on Distribution of Potential 31, 265

S.

SALIENT Poles 118
Sankey's Iron of High Permeability 85, 86, 100
Saturation, Curves of 524, 587, 602, 615, 626
„ Magnetic 82
„ of Pole Horns 258, 263, 268
„ of Teeth 146, 533, 545, 560, 566
Sawyer's Inductor Dynamo 15
Saxton's Early Machines 10
Sayers on Auxiliary Poles 262
„ on Boosters 788
„ Commutator Coils 66, 270
„ Electro-plating Dynamo 707
„ on Motor Commutation 827
„ on Parallel Running 927
Schellen on Theory of Dynamo 6
Schuckert's Dynamos 22, 269
Schultze on Cross-Magnetization 258
Schulz, Workshop Tools for Dynamo Construction 422
Schmidt, E., on Iron for Magnetic Purposes 90
Schedule for Costs 581
„ for Dynamo Design 579
„ for Magnetic Calculations 152, 580, 585, 600
Scott & Mountain, Generators 663
„ „ „ Analysis of Design 583

PAGE

Scott & Mountain, Generators, Flux-Densities used by 665
„ „ „ Magnet Bobbin, Description of .. 665
„ „ „ Test Curves of 594
„ „ „ Use of Equalizing Rings 665
„ „ „ Winding Diagram of 666
Scott's Rubber Varnish 190
Scott, E. Kilburn, on Armature Construction 422
„ „ on Electro-metallurgical Machines 721
„ „ on Cost of Machines 573
Search-Lights Introduced 15
Seatings for Armature Spiders 431, 473
Secondary Losses 219, 234, 444, 523
"Section" of an Armature Winding 281, 364, 448, 449, 462
Segmental Core-Disks 58, 423
Segments of Commutator, Forms of .. .. 486 to 493
„ „ Nature of 53, 482
„ „ to find Number of 482, 556
Self-Compensating Armatures 270
Self-Exciting Principle, History of 15, 16
Self-Induction, Effects of.. .. .. 218, 251, 273, 750
Sellers, Coleman, on Double Lubrication 478
„ „ on Seatings of Bearings 477
Sellon, R. P., on Continuous-Current Transformation 774
Separate Coils for Excitation 15, 65
Separate Excitation by Battery 8, 11, 62, 705
„ „ by Exciter 12, 14, 62, 705
Separately-Excited Dynamo, Invention of .. 8, 11, 12, 14, 62, 705
„ „ „ Theory of 290, 295
„ „ „ Use in Electro-plating 705
Separation of Losses 922
Series-Dynamo 64, 299, 322, 346
„ „ Characteristic of 322, 346
„ „ Coupling of 928
„ „ Unfit for Electro-plating 64, 706
Series-Grouping (i.e. two-circuit multipolar) in Armature Winding
359, 363, 369, 378, 383, 408, 410, 411, 466
Series-Lighting 346
Series Motors, Characteristics of 816
„ „ in Transmission 800, 820
Series-Parallel Arrangement of Two Motors 840
„ Controller for 889
„ Grouping of Winding on Armatures
359, 365, 369, 378, 408, 410, 411, 466, 558
Series-winding on Motors .. .. 816 to 821, 832
Shaft, Design of 472
Shaping of Pole-Pieces .. .. 263 to 270, 571, 686, 691

PAGE
Shellac as Insulator 189, 193, 194
„ and Mica (Micanite) 190, 195, 487
Shifting of Brushes 216, 238, 745
Short, Prof. Sidney H., on Dynamo Design 535
„ „ „ Motor Armature 859
„ „ „ Reaction Brush-holder 509
„ „ „ Standard Generators, designed by 691
„ „ „ Walker Co.'s Machine, designed by 595
Short-Circuiting during Commutation 236, 239
Short-Circuits in Armatures 934
„ „ in Magnet Coils 938
Shunt 64
Shunt-Coil Calculation 168, 170, 527, 589
„ Heating of 183, 518
Shunt-Current, Calculation of 300, 518, 527, 589, 605, 618
Shunt Dynamos, Characteristics of 336 to 344
„ „ Coupling of 927
„ „ Efficiency of 302, 553, 619
„ „ Formulæ for 300
„ „ History of 11, 17, 64
„ „ Regulation of 307
„ External, for Adjusting Compound-winding 319, 531, 697
„ Motors, Characteristics of 824
„ „ Properties of 821
„ Resistance, Calculation of 302, 531
Siemens, Alexander, on Shunt Dynamo 337
Siemens, Sir William, on Compound Winding 33
„ „ Early Researches 13, 22
„ „ Efficiency of Motors 801
„ „ on Shunt Dynamo 22, 337
„ „ on Transmission of Power 800
Siemens, Werner von, on Armature Reaction 25
„ „ „ Efficiency of Motors 800
„ „ „ Homopolar Dynamo 766
„ „ „ Invents Term *Dynamo-Elektrische Maschine* 17
„ „ „ Self-Exciting Principle 16
„ „ „ Shuttle-wound Armature 13, 14, 19
„ „ „ on Transmission of Power 800
Siemens Bros'. Alternators 122
„ Dynamos 19, 21, 323, 329
„ Generator at Paris Exhibition 22
Siemens & Halske, Brush-holders 504
„ „ Drum-Armatures 444
„ „ Electro-plating Machines 706
„ „ Evolute Winding 446

PAGE

Siemens & Halske, Generators 19, 20, 121, 133, 687, 699
„ „ Inner-Pole Type of Generator 21, 464, 687
Silk as Insulator 189, 442
Silver, Deposition of 8, 724, 725
Silver Solder for Armatures 446
Sinsteden, F., Early Researches 11–13
„ Method of Concatenating Machines 12, 705
„ „ of Separate Excitation 11
„ on Self-Exciting Dynamo 13, 15
Size in Relation to Output 535
Slate as Insulator 193
Sliding Conductors, Electromotive-Force of 290, 767
„ Contacts 767
„ Rails 49, 930
Slip-Rings 49, 660, 690, 762
Slots in Armature 423, 425, 426, 560, 567
„ Arrangement of Conductors in
401, 403, 447, 448, 465, 560, 565, 567, 656, 658, 680
„ Calculation of 161, 403, 559, 636, 680
„ Depth of 636, 646, 656, 681
„ Insulation of 161, 162, 193, 195, 560, 636, 646, 663
„ Number of 403, 465, 559, 646
„ Space-Factor for 160, 161, 561, 681
Smit, W., Brush-Gear 512
Smith, Rev. F. J. (*see Jervis-Smith*).
Smith, Willoughby, on Homopolar Dynamo 767
Smooth-Core Armatures 18, 426, 439
Snell, A. T., on Motors 792
Space-Factor in Armatures 160, 561, 681
„ in Magnet Coils 162
Sparking, Cause of 235
„ Criteria of 275
„ Prevention of 239, 255, 272
Sparking-Voltage 250
Specific Gravity of Alloys 902
Specific Load (Amperes per Inch of Periphery) 276, 542, 634, 644, 678
Specific Utilization, Coefficient of 575
„ „ Discussion of 700
Specification of Generator 534, 554, 583, 632, 654, 678
„ of Motor 851
„ of Rheostat 871
Speed, Advantage of High Peripheral 576, 700, 702
„ Dependence of Volts on 59, 281, 290, 291, 330, 339, 767
„ Peripheral, Usual Values 536
„ in Relation to Characteristic 330, 339
„ and Torque in Motors 810

PAGE
Speed Variable, in Motors .. 838
„ Variation of, with Size .. 535
Spherical Armature .. 54, 742
„ Bearings .. 476
Spiders for Armature .. 428, 433, 434, 640
Spiral Winding .. 209, 352, 358
Split-Tube Commutator .. 10, 45
Sprague, F. J., on Motor Regulation .. 897
Spurious Resistance .. 217
Stabilit .. 194
Staggered Brushes .. 500
„ Pole-Pieces .. 269, 571
Stampings for Cores .. 423 to 427
Starters for Motors .. 874
Starting of Dynamos .. 931
„ of Motors .. 874
Steam Consumption Tests .. 924
Steam-Turbine Generators, Design of .. 702, 756
Steatite .. 189
Steel, Magnetic Properties of .. 84, 89, 98, 100
„ Mild Cast for Magnets .. 84, 89
„ Tensile Stress of, for Binding Wires .. 440
Steinmetz, C. P., Coefficient of Output .. 537, 544
„ Law of Hysteresis .. 99
„ on Strength of Dielectrics .. 196
Sterling Varnish .. 189, 194, 442
Stiffness of Field .. 255, 277
Stiffness-Ratio as Criterion of Design .. 277, 608, 631
Stöhrer's Early Machines .. 10
Stoneware .. 190
Stranded Copper Conductors .. 25, 160, 444
Stray Field .. 131, 141
„ Power .. 219, 234, 444, 523
Street-Tramway Generators 554, 595, 632, 652, 654, 664, 669, 671, 675, 683, 686, 691, 695, 697, 699
„ Controllers .. 885
„ Motors .. 858
Stress, Effects of, on Magnetism .. 90
„ Tensile, of Binding Wires .. 440
Stresses in Shafts .. 472
Stroh, A., Constructs Self-Exciting Dynamo .. 17
Stromberg, on Armature Reaction .. 258
Sturgeon, Wm., Early Machine and Commutator .. 10
„ First uses Machine for Electro-deposition .. 704
Sturtevant Co's. Motor Starters .. 877
Subdivision of Armature Winding .. 52, 288

PAGE

Sulphur as Insulator 189
Surface, for Heat Emission, in Armatures 186, 559, 576
„ „ „ in Commutators 520, 593
„ „ „ in Magnet Coils 169, 182
„ Speed in Relation to Cooling 186
„ Windings 49, 420, 430, 443, 462
Swinburne, James, on Armature Exploration 203
„ „ on Armature Reaction 257
„ „ on Armature Compensation 263
„ „ on Dynamo-Testing 920
„ „ Chord Winding 354
Symbols, Explanation of 6, 73, 81, 131, 145, 278, 280, 365, 367, 369, 541

T.

TABLE of Allotment of Costs of Material 573
„ of Apportionment of Losses 552
„ of Binding Wires in Bipolar Dynamos 441
„ of Calculation of a Magnetic Circuit 152
„ of Connexions to Equalizing Rings 415
„ of Current-Carrying Capacities of Wires 903
„ of Dielectric Strength of Insulating Materials 193
„ of Dispersion Coefficients 137
„ of Drum-Armature Winding 355, 361, 372
„ of Effects of Joints in Magnetic Circuit 94
„ of Excitation Losses 518
„ of Fluxes in Various Parts of Generator 136
„ of Hysteretic Constants for Different Materials 100
„ of Insulating Materials 189
„ of Loss of Power in Copper Conductors 181
„ of Lost Volts in Percentage of Full-Load Pressure 525
„ of Magnetic Data 88, 89
„ of Output Coefficients 540
„ of Peripheral Speeds in common use 536
„ of Puncture Tests 195
„ of Resistance of Copper at Different Temperatures .. 156
„ of Resistance-Materials for Rheostats 903
„ of Sizes of Journals 471
„ of Specific Utilization Coefficients 701
„ of Statistics of Electro-deposition of Metals 723
„ of Suitable Current-Densities in Electro-deposition 725
„ of Symbols 280
„ of Triplex Winding 398
„ of Typical Permissible Full-Load Losses 553

PAGE
TABLE of Usual Flux and Current Densities 545
„ of Voltages Required in Electro-deposition 724
„ of Waste of Power by Eddy-Currents.. 104
„ of Waste of Power by Hysteresis 102
„ of Wave-winding 372, 401
Tangential Pull on Armature 223, 230, 812
Tape, Insulating 174, 193, 196, 454, 561
Tatham, on Dynamometry 918
Teazer Coils 706
Teazers, or Reducers (*see* Reducers).
Teeth, Density of Flux in 146, 545, 600, 860
„ Estimation of Flux-Density in 146
„ Number of, in Relation to Noise 939
„ Produce Eddies in Pole-face 23, 154, 221
„ Shapes of 425, 427, 465
„ Width of, in Relation to Width of Slots 465
Temperature, Electrical Measurement of 159, 581, 682
Temperature-Rise, Estimation of .. .. .. 183 to 188, 520
„ „ Permissible 188, 632, 914
„ „ (*see also* Heating).
Terminal Voltage .. 291, 293, 299, 301, 304, 310 to 317, 326, 348, 644
Terminals of Magnet-Coils 175
Testing Dynamo 913
„ „ for Efficiency 914
„ „ for Faults in Armature 934
„ „ for Insulation Resistance 914
„ „ for Resistance to Puncture 914
„ „ for Temperature-Rise 581, 914
Testing Motors 913
Tests of Combined Plant 924
Tests, Schedule of 578, 581
Theory of Armature-windings 350
„ of Binding Wires 440
„ of Commutation by Reversing Field 238
„ „ „ by Contact Resistance 240
„ of Compound-wound Generators 314, 928
„ of Continuous-Current Transformers 775
„ of Constant-Potential Dynamos 304
„ of Dynamo 279
„ of Magnetic Circuit 76, 108
„ of Motors 797
„ of Self-Regulating Dynamo 309
„ „ Motors 831
„ of Series-wound Generators 299, 927
„ of Shunt-wound Generators 300
Thickness of Air Gap 154, 550, 562, 637, 656, 681

PAGE
Thickness of Core-Disks .. 99, 105, 423, 517, 590
,, of Mica Slips in Commutator .. 486, 488, 564, 690, 753
,, of Shunt Wires .. 168, 170
,, of Slot-Insulation .. 161, 193, 195, 196, 561, 636, 665
Third-Brush Method of Regulation .. 65, 763
Thomas, Eustace, on Commutation .. 36
Thomson, Prof. Elihu, Arc-Lighting Dynamo .. 742
,, ,, on Armature Compensation .. 265
Thomson, M. E., on Armature Distortion .. 207, 265
Thompson, S. P., on Exploration of Armature .. 203
,, ,, Methods of Remedying Distortion .. 263, 265
,, ,, Method of Governing Motor .. 848
Thomson-Houston Co., Arc-Lighting Machine .. 742
,, ,, ,, ,, Armature of .. 742
,, ,, Armatures of Generators .. 459
,, ,, Carbon Brush-holder .. 505
,, ,, Equalizing Rings used by .. 414
,, ,, Motor Armature .. 860
Thomson, Prof. James, on Brake Dynamometer .. 917
Three-Wire Dynamos .. 763
Three-Phase Currents from Dynamo .. 660, 690, 762
Thrust-Bearings .. 476
Thurston, Prof. R. H., on Brush Dynamo .. 742
Thury, Automatic Regulator .. 873
,, Boosters .. 788
,, Continuous-Current Machines for Transmission .. 754
,, Extra High-Voltage Generator .. 754
,, Electrolytic Generators .. 717, 718
,, Railway Motor .. 863
,, Vertical Shaft Motor for Pump .. 866
Timmermann, A. H. & C.E., on Temperature-Rise in Armatures 186
Torque of Armatures .. 227
,, Definition of .. 227
,, of Motors .. 808
,, Relation of Torque and Speed .. 227, 808
,, at Starting .. 875
Toothed Core-Disks .. 55, 221, 424, 427
Traction Generators .. 595, 632, 654
,, Motors .. 858 to 866
Tramway Generators .. 595, 632, 654
,, Motors .. 858 to 866
Transformation Ratio .. 775
Transformers for Continuous-Currents .. 772
Transmission of Energy .. 800, 820
,, ,, High-Voltage Machines for .. 754
,, ,, by Two Series Machines .. 820

PAGE
Transmission of Energy by Two Shunt Machines 824
Trial-Values in Design .. ..545 to 564, 852, 860
„ for Diameter and Length of Armature Core 536, 555, 633
„ for Number of Commutator Segments 549, 557
„ for Number of Conductors 548, 556
„ for Number of Poles 545, 554
„ for Size of Magnet Cores 562
Triplex Winding 367, 398
Trotter, A. P., on Motor Regulation 870
„ Regulator 894
Turbine, Steam, Design of Generators for .. 702, 722, 756, 759
„ Water, „ „ 31, 709, 713, 717
Turning Moment (*see* Torque).
Two-Commutator Dynamos 367, 609, 706, 718, 721, 722
„ Motors 863
Two-Circuit Multipolar Winding (*see* Series-Grouping).

U.

UMBRELLA-TYPE of Machine 31, 662, 709, 715, 717
Under-Type Bipolar Machine 14, 24, 25, 117
Unidirectional Current 10, 51, 731
Unipolar Dynamo (*see* Homopolar).
Units, Magnetic 71, 81
„ Relations between 228, 281
Unwin, Prof. W. C., on Brake Dynamometer 916
„ „ on Machine Design 467, 473
Uppenborn, on Homopolar Dynamos 768
Utilization, Specific, of Material 575, 701

V.

VACUUM Drying Chamber 196
Van Malderen's Early Machines 13
Varley, Cornelius & Samuel A., Self-Exciting Dynamo 16
Varley, Cromwell F., on Continuity of Current 285
Varley, F. H., Early Machine 16
Varley, O., Early Machine 16
Varley, Samuel A., Compound Winding 16, 33
„ „ Early Machines 16, 33
„ „ Homopolar Dynamo 766

PAGE

Varnish "Armalac" 190
„ "Enamelac" 190
„ Japan 190
„ Mode of Applying 194
„ "Scott's Rubber" 190
„ Shellac 189
„ "Sterling" 190, 194, 442
Ventilating Ducts, Allowance for 144, 637
Ventilation of Armatures 438
„ of Commutators 520
„ of Field-Magnets 178
Ventilators 428
Vertical Shaft Generators 31, 476, 478, 709, 713, 717
„ Motors 886
Vibration and Noise 939
"Victoria" Dynamo 28, 29
Vitrite 189
Vincent's Early Machine 24
Voltage Required in Electro-deposition 724
Voltage-Drop 293, 304, 306, 336, 525
Volume of Armature 536
„ of Magnetizing Coil 165, 167
Vulcabeston 189, 193
Vulcanized Fibre 189, 193

W.

Walenn, W. H., on Reversibility of Dynamo 34
„ on Electro-deposition 705
Walker, Miles, on a Magnetic Permeability Meter 90
Walker Co's. Traction Generator 595
Waltenhofen, A. Von, on Theory of Dynamo 32
Warburg, Professor E., on Loss per Magnetic Cycle 97
Waste of Power in Copper 181
„ in Excitation 169, 518, 552, 553, 591
„ in Iron .. .. 99 to 106
Watkins, F., Early Machine 10
Watt, The, Unit of Power 229, 296
Wave-winding, Balancing Circuits for 415
„ „ of Drum Armatures 360, 371, 375
„ „ Examples of .. 372, 383, 392, 401, 558, 654, 671, 753
„ „ Peculiarities of 382, 405, 408, 558
„ „ Rules for 363, 364, 371, 378, 383, 408
Webber, Maj.-Gen., C. E., on Motor-Generators at Chelsea .. 773

PAGE
Weber, Wilhelm, on Laws of Induction 31
„ „ on Unipolar Induction 766
Wedding, Prof., on Dispersion 138
Weights of Generators in Relation to Speed and Cost 573
Weights of Copper, Calculation of 155, 171
Westinghouse Co. Air-Blast for Cleaning 932
„ Alternators 30, 31
„ Arc-Light Machine 748
„ Brush Gear 511
„ Construction of Armatures 426, 453
„ Controller 894
„ Electrolytic Generators 721
„ Multipolar Generators 120, 721
„ Use of Copper Dampers 107
Weston, E., Early Machines 22, 117, 705
Wheatstone, Sir Chas, Early Machines 11, 15, 17, 33, 705
„ „ Suggests Separate Excitation by Battery 11, 705
„ „ on Self-Exciting Dynamos 17, 705
Wheeler, Dr. S. S., on Parallel Running 928
„ „ on Space-Factor and Bedding of Wires .. 164
Width of Slot 560, 635
„ of Tooth 560, 635
Wiener, Alfred, on Dispersion 141
„ „ on Dynamo-Machines 138
„ „ on Estimation of Number of Poles 546
Wilde, Dr. H., Concatenation of Machines 14, 705
„ „ Discovers Synchronous Control of Alternators .. 15
„ „ Early Machines 14, 15
„ „ Electro-Magnetic Generator 14, 115
„ „ Form of Multipolar Field-Magnet 15, 120, 122
„ „ Introduces his Machines for Electro-plating .. 705
„ „ Introduces Searchlights 15
„ „ Makes Alternator Self-Exciting 15
„ „ Multipolar Machines 15, 120, 122, 705
Willans's High-Speed Engines 738
Willesden Paper 189
Williamson on Motor Equipments 846
Wilson, Prof. E. 573
Windage Loss 520, 552, 553
Winding of Armatures, Bar 442
„ „ Barrel Drum 448
„ „ Bastard Drum 452
„ „ Choice of 407, 415, 558
„ „ Duplex 367, 397
„ „ Evolute Drum 446
„ „ Formers for 453, 457